DEVELOPMENT OF A NEW METHODOLOGY

FOR ROCK ENGINEERING DESIGN

Final Technical Report

By

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ABSTRACT

The research conducted for this contract was aimed at developing a new methodology for rock engineering design using a systems approach termed "Rock Engineering Systems" (RES). The basis of this 'top-down' approach is to first establish the engineering objective(s), and then construct a diagram, an interaction matrix, in which all the variables relevant to the problem are listed, together with their interactions. The matrix device enables all the interactions, or mechanisms, to be coherently and comprehensively identified. Mechanism pathways through the interaction matrix enable all potential concatenations of mechanisms and consequences to be listed. The work was successfully completed following the objectives and milestones in the contract.

The flow charts for the design methodology were improved following further literature study and research in the first year. Also, the link between this interaction matrix approach and the maths associated with set theory, matrix theory and network theory was clarified in the first year. In the second year, the problem of computerizing the methodology was addressed. In the third year, the methodology was refined and successfully tested on a surface site (rock slopes in Spain) and an underground site (the AECL Underground Research Laboratory in Canada). Thus, the Rock Engineering Systems design methodology was successfully developed.

As a result of the research, two PhD degrees were obtained directly on the work in the contract (completed in 1993, see Appendices A & B), two MSc degrees were obtained (in 1992) and a further two PhD degrees expected this year (1994, see Section 6 of this Report) have been significantly influenced by the work.

LIST OF KEYWORDS

Civil engineering
Coupled mechanisms
Design
"Rock Engineering Systems" (RES)
Rock mechanics
Rock engineering
Site investigation

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1. INTRODUCTION AND STATEMENT OF OBJECTIVES

As the subjects of rock mechanics and rock engineering continue to expand, we are faced with increasing complexity of information and increasing difficulty in deciding how to engineer new structures. This has occurred both as a result of more complex analyses of 'precedent practice' engineering, such as dams, shafts and caverns, and the introduction of newer types of engineering such as geothermal energy, radioactive waste disposal and all kinds of innovative uses for underground space.

In any rock engineering problem, there is a multitude of rock properties that could be measured. Similarly, there is a multitude of proposed rock mechanics mechanisms that can be invoked, and the structure can be designed to defend against many types of potential collapse mechanisms. Furthermore, all these properties and mechanisms influence one another to a greater or lesser extent. One is faced, therefore, with making a decision in an increasingly complex world on how to proceed from the original "top of the flowchart" rock engineering requirement.

In order to identify and present the interactions between rock mechanics and rock engineering factors in these conditions, the use of rock mechanics interaction matrices was developed. This method for considering the interactions between rock properties and the construction process was initially described in the monograph "Rock Mechanics Principles in Engineering Practice" [1] and was developed to try to introduce some coherency into studying the interactions between the rock engineering factors. The method is briefly described in the next section.

It has become apparent that this approach, tentatively called "Rock Engineering Mechanism Information Technology", REMIT, is, in fact, a sub-set of a far wider set of procedural and analysis techniques based on information technology. This Report describes the development of a procedure to enable a client, engineer, contractor or researcher to decide for any project the relevant rock properties and their priority, relevant boundary conditions, rock mechanics mechanisms that should be studied, the interaction between these, and hence the overall type and sequence of site investigation, analysis, design, construction and monitoring that should be conducted for optimal use of the resources available. As this is a vast subject, the research was explicitly focussed on the development of the basic methodology extending the interaction matrices and using the link with set theory, object-oriented programming, C++, etc.

The material presented in the next section outlines the technique as it has been initially applied to the factors involved in cavern design.

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[1] FOOTNOTE Hudson, J A, "Rock Mechanics Principles in Engineering Practice" published by Butterworths, London, 1989, for CIRIA.

Background to the Research

In order to place the reported results and appended theses into context, the background material to the research carried out by the Rock Engineering Group at Imperial College, London, UK and Rock Engineering Consultants during 1991-1993 is reviewed below.

Some diagrams are presented to explain the overall background to the general rock engineering problem and the difficulty of:

a) knowing what rock properties are involved,
b) what rock failure mechanisms might be involved,
c) what effect construction will have on the previous two.

There are many corollaries to these difficulties. What should be measured in a site investigation for optimal use of the resources? What is the best geometry of the structure? How should this be orientated with respect to the rock mass structure? What sort of analysis should be conducted? Have all possible failure mechanisms been taken into account? Etc. The interaction matrix developed by Hudson was a first attempt to come to grips with the complexity of the situation - especially, to identify the interactions between the relevant parameters.

To provide an initial overview approach to the whole problem, Fig.1 is a generic diagram illustrating all rock engineering projects. The three border rings illustrate the various levels of considering the project from the outer ring representing the overall problem, through the middle ring in which interactive mechanisms are considered, to the central ring in which each component factor of the problem is considered separately.

In designing structures to be built on or in rock, four of the main factors to be considered are the rock mass structure, the *in situ* rock stress, the water flow and the construction procedures. Some of the complexities and interactions between these main factors are illustrated in Fig. 2 for the case of an underground opening. This diagram vividly demonstrates the need for some coherent method of identifying and studying the interactions between the main factors is required.

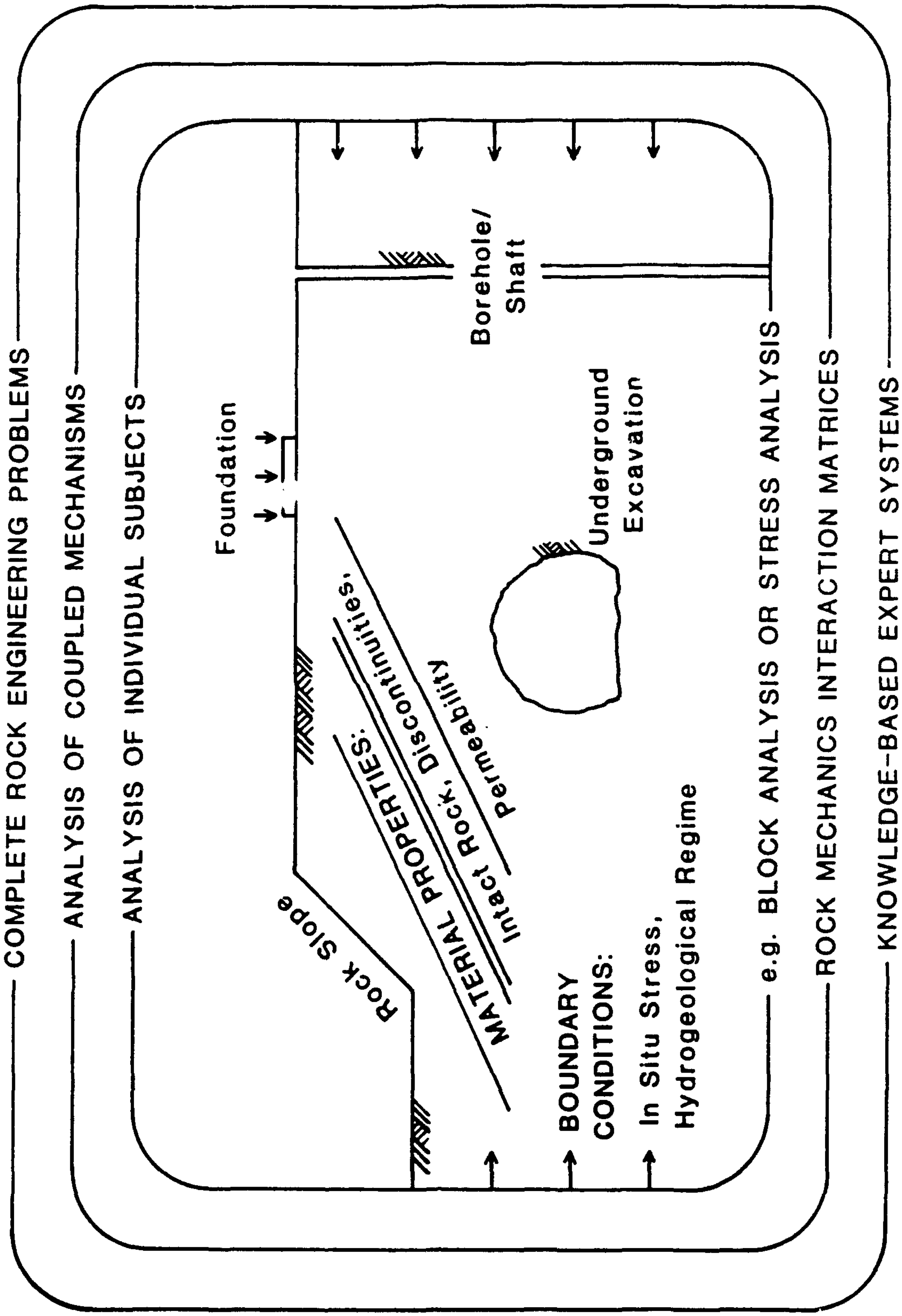


Figure 1. General diagram illustrating all rock engineering problems; border rings represent the overall problem (outside ring) to specific sub-problems (inside ring).

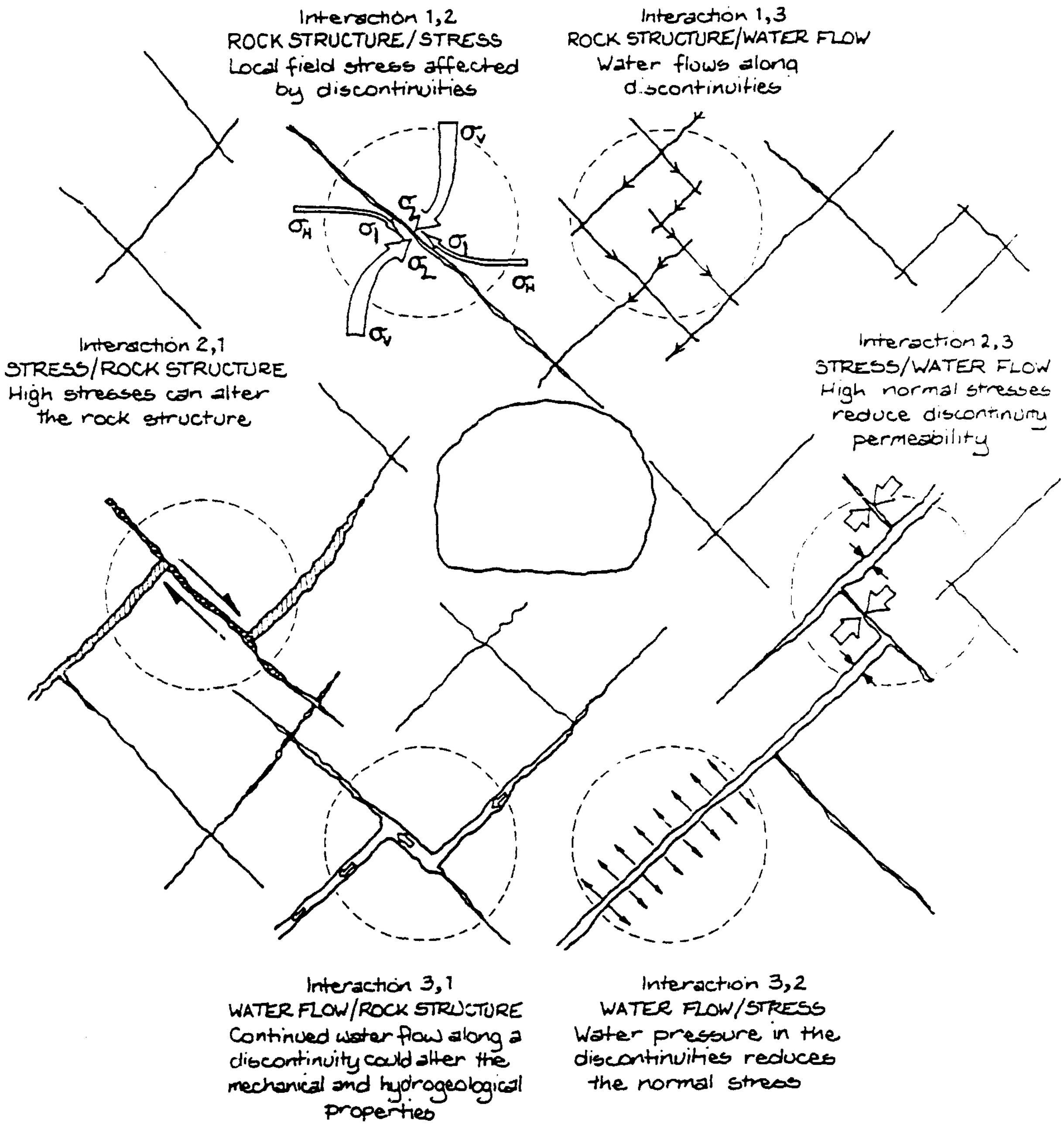
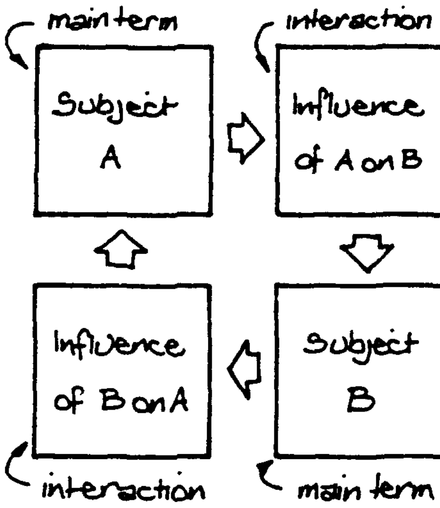


Figure 2. Interaction of primary factors (Rock structure, rock stress, water flow and construction) around an underground opening.



The method of identifying the interactions is through a new method — the interaction matrix — developed recently. The main factors are listed along the diagonal (top left to bottom right — the leading diagonal) as indicated on the 2x2 matrix above. The influence of one factor on another can then be studied in the off-diagonal boxes.

In the general case illustrated in Fig. 3, there are four main factors and twelve interactive terms — indicating that it would be very difficult to study all these coupled factors without some form of coherent structure. The case is only one example of a whole host of possible such presentations and analyses that could be derived from them. For example, the three main forms of slope instability in rock are plane failure, wedge failure, and toppling failure. These could be along the leading diagonal with the interactive terms indicating how one type of failure could lead to another — and in fact represent the texture of a blasted rock face that one often sees. Similarly, on a smaller scale, the diagonal terms could be Modes I, II & III of rock fracture, with the off-diagonal terms being all binary combinations of mixed mode fracture.

It follows from this that some form of structure is required for analyzing all rock engineering information — and this lead to the "System Flowchart" overleaf. This is the basis for a Rock Property Information Technology approach to the subject of rock properties. (The research reported here has a wider scope because it includes rock mechanisms and the design process itself).

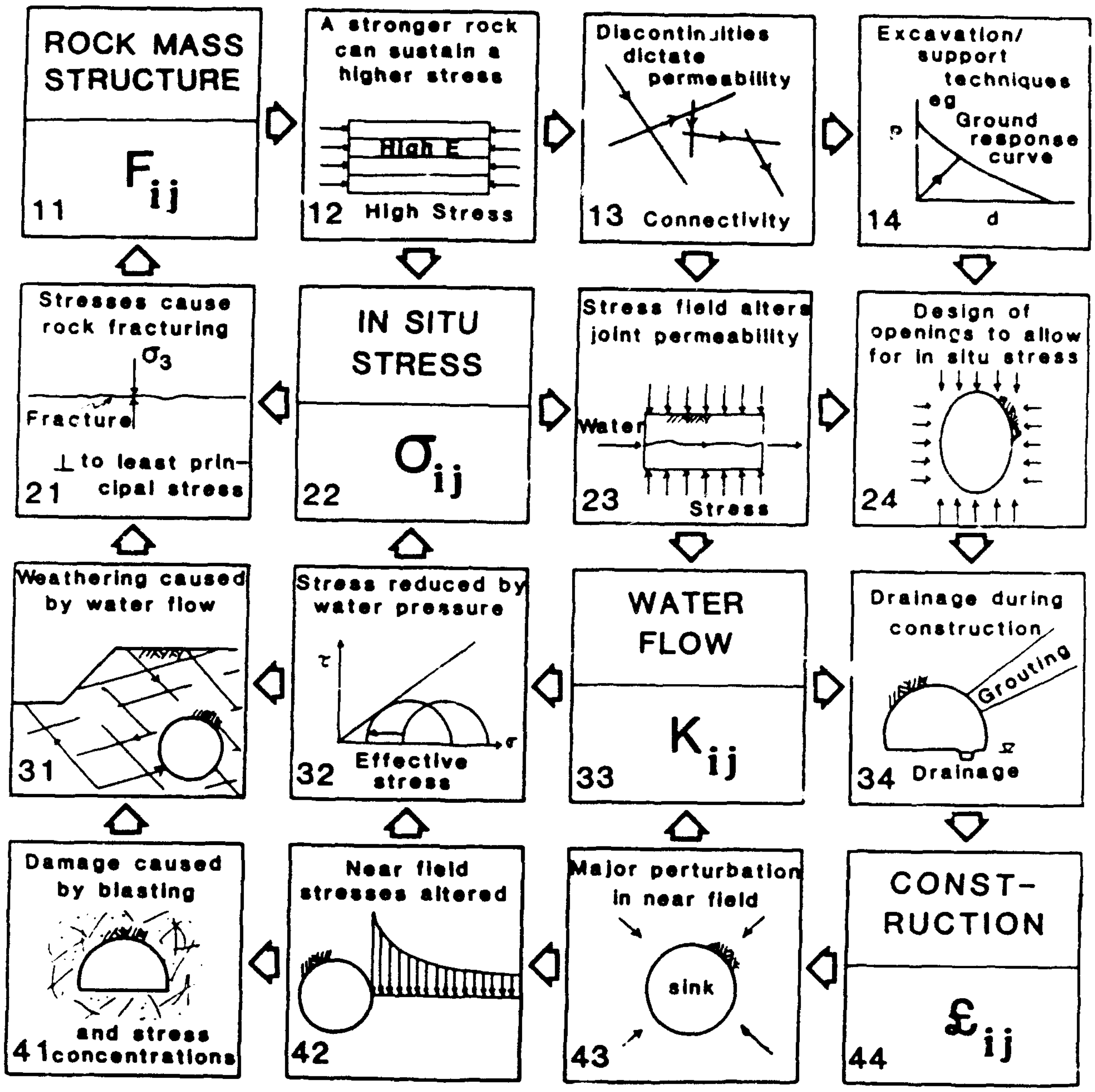


Figure 3. Rock mechanics interaction matrix illustrating the primary factors (along the leading diagonal) and the interactive coupled factors (in the off-diagonal boxes).

SYSTEM FLOWCHART

LEVEL 1

A. Literature Analysis
B. Precedent Practice & Existing Practice
C. Suggested Practice

LEVEL 2

EACH SPECIFIC PROBLEM

e.g. Pressure Tunnels
Radioactive Waste Disposal
Large Underground Caverns

LEVEL 3

MAIN GROUPINGS OF PARAMETERS

Intact Rock	Discontinuity	Rock Mass	Site	Project Location

LEVEL 4

BEHAVIOURAL GROUPING OF PARAMETERS

Intact Rock	Discontinuity	Rock Mass	Site	Project Location
Composition	Geometrical	Composition	Heat	Engineering Dimension
Conditions	Conditions	Conditions	Hydro	Excavation Type
Deformation	Deformation	Deformation	Stress State	Rock Stabilization
Strength	Strength	Strength	Location	Monitoring
Post Peak	Post Peak	Post Peak		Finance
Time Dependent	Indicators	Time Dependency		
Indicators		Indicators		

LEVEL 5

MAIN OVERALL PARAMETERS

Intact Rock	Discontinuity	Rock Mass	Site	Project Location
Macrostructure	Dimensional	Physical	Temperature	Geometrica
Microstructure	Surface	Geometrical	Heat Flow	Excavation Method
Aspects of Heat	Descriptive	Block Characteristics	Water Pressure	Excavation Performance
Aspects of Water	Separation Characteristics	Aspects of Water	Water Flow	Rock Support & Reinforcement
Linear Elastic	Filling Properties	Elastic	Boundary Conditions	Water Control
Non Linear Elastic	Aspects of Water	Compressive	Water Chemistry	Observational Techniques
Not Elastic	Elastic	Shear	Intact Rock	Field Tests
Compressive	Shearing Characteristics	Failure Criterion Parameters	Discontinuity	Costs
Tensile	Compressive	Failure	Thermal	
Shear	Shear	Creep/Relaxation	Location	
Hardness	Hardness	Rock Quality	Component	
Rock Fracture	Failure	Geophysical	Conditions	
Failure	Geophysical	Large Scale Geological - Features	Sources	
Creep/Relaxation			Insitu Stress State	
Durability			Position	
Swelling Potential				
Geophysical				

LEVEL 6

DETAILED PARAMETERS

Separation Characteristics — Aperture
Filling Type
Filling Thickness

LEVEL 7

INFORMATION WITHIN DETAILED PARAMETERS

Aperture —

APERTURE	DESCRIPTION
<0.1mm	Very tight
0.1-0.25 mm	Tight
0.25-0.5 mm	Partly open
0.5 2.5 mm	Open
2.5-10 mm	Moderately wide
>10 mm	Wide
1-10 cm	Very wide
10-100 cm	Extremely wide
>1 m	Cavernous

In accordance with ISRM Suggested Methods, Rock Characterization Testing & Monitoring 1981

Level 1 indicates whether the approach is to be based on the literature, existing practice, or suggested practice — with the attendant advantages and disadvantages

Level 2 is the problem itself, what are we trying to do?
Level 3 is the main groupings of parameters
Level 4 is the 'behavioural' groupings of parameters, i.e. the main overall groups
Level 5 is the main overall parameters
Level 6 is the detailed parameters

One example of how the system flowchart has been used is for underground caverns. Let us say that we wished to know what rock properties are important for the design of rock caverns, what the prioritization of these properties or parameters was, and how these properties interacted. This particular problem was studied using the approach resulting in the following diagrams.

The first approach involved the information supplied by the literature, i.e. by looking at 110 recent papers on the design of underground caverns. The papers studied are shown in the top diagram in Fig. 4, their purpose in the middle diagram and their sizes on the bottom diagram. It was then possible from the papers to study how often the Level 5 parameters had been studied in the papers as shown on Fig.5, with the histogram bars being shaded according to the Level 4 groupings.

From the histogram in Fig. 5, it can be seen, for example, that from the literature, the 10 most important parameters for cavern design are:
depth of the cavern, fracture orientations, stress magnitude, stress direction, fracture frequency, rock mass geometry, fracture apertures, presence of faults, compressive strength of the intact rock and deformability of the rock mass.
This exercise can, of course, be conducted for any of the three Level 1 approaches and for any Level 2 subject.

Moreover, a large interaction matrix can be easily constructed via the data base (IBM compatible REFLEX was used for this) as illustrated in Fig. 6. This is simply a very large extension of the concept in Fig. 3 but considering how often the parameters have been studied together - with the 31 Level 4 parameters along the leading diagonal. The contouring indicates how often the interaction of the parameters has been studied, with the shading indicating the relative frequency.

The diagram becomes more clear when the 31 Level 4 parameters are ordered according to their priority, as has been done in Fig. 7. It was at this stage that the relation with set theory became evident by considering the architecture of the interaction matrix - the two sides of the matrix being quite different in their form.

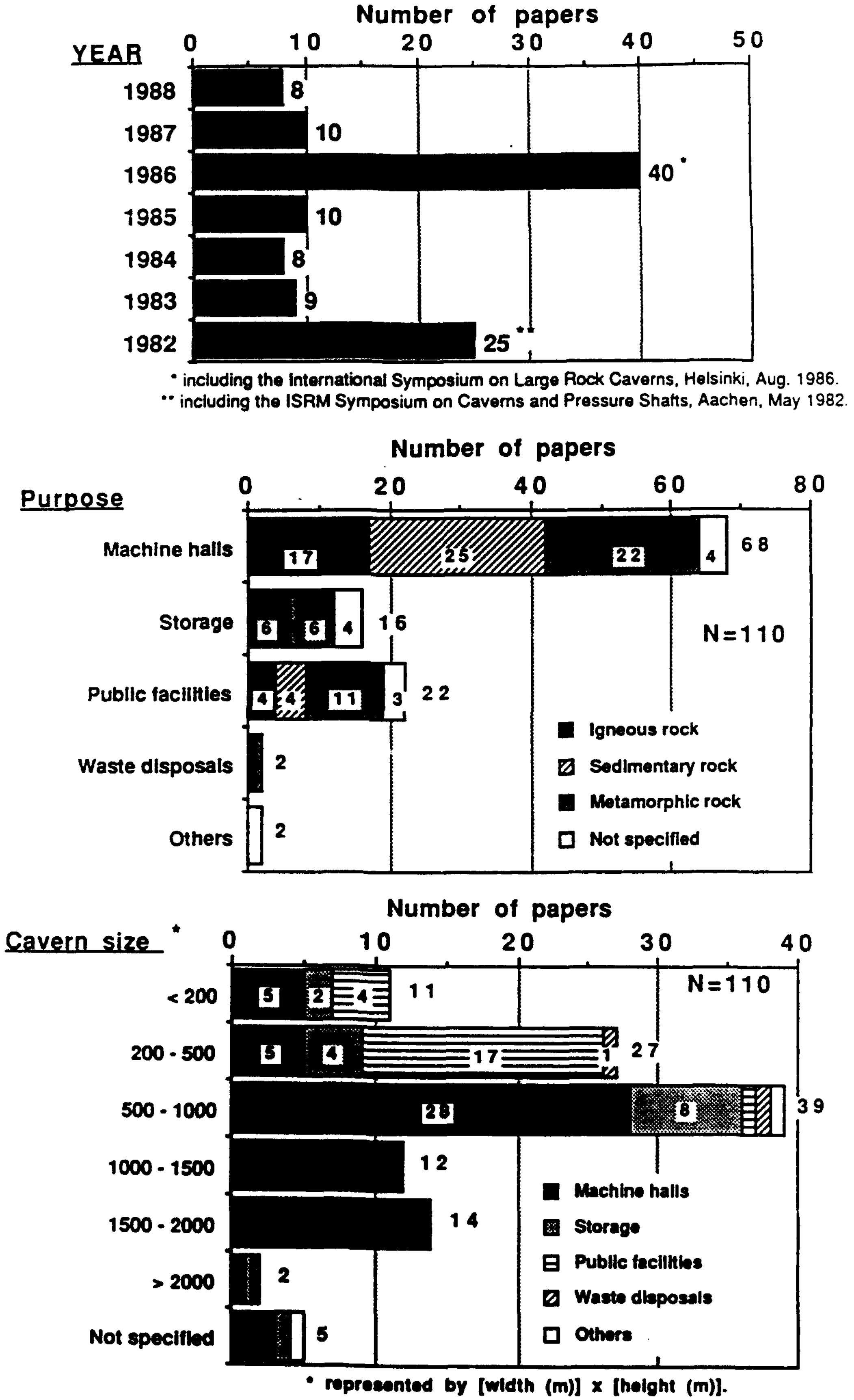


Figure 4. Histograms showing details of papers studied for rock parameter prioritization.

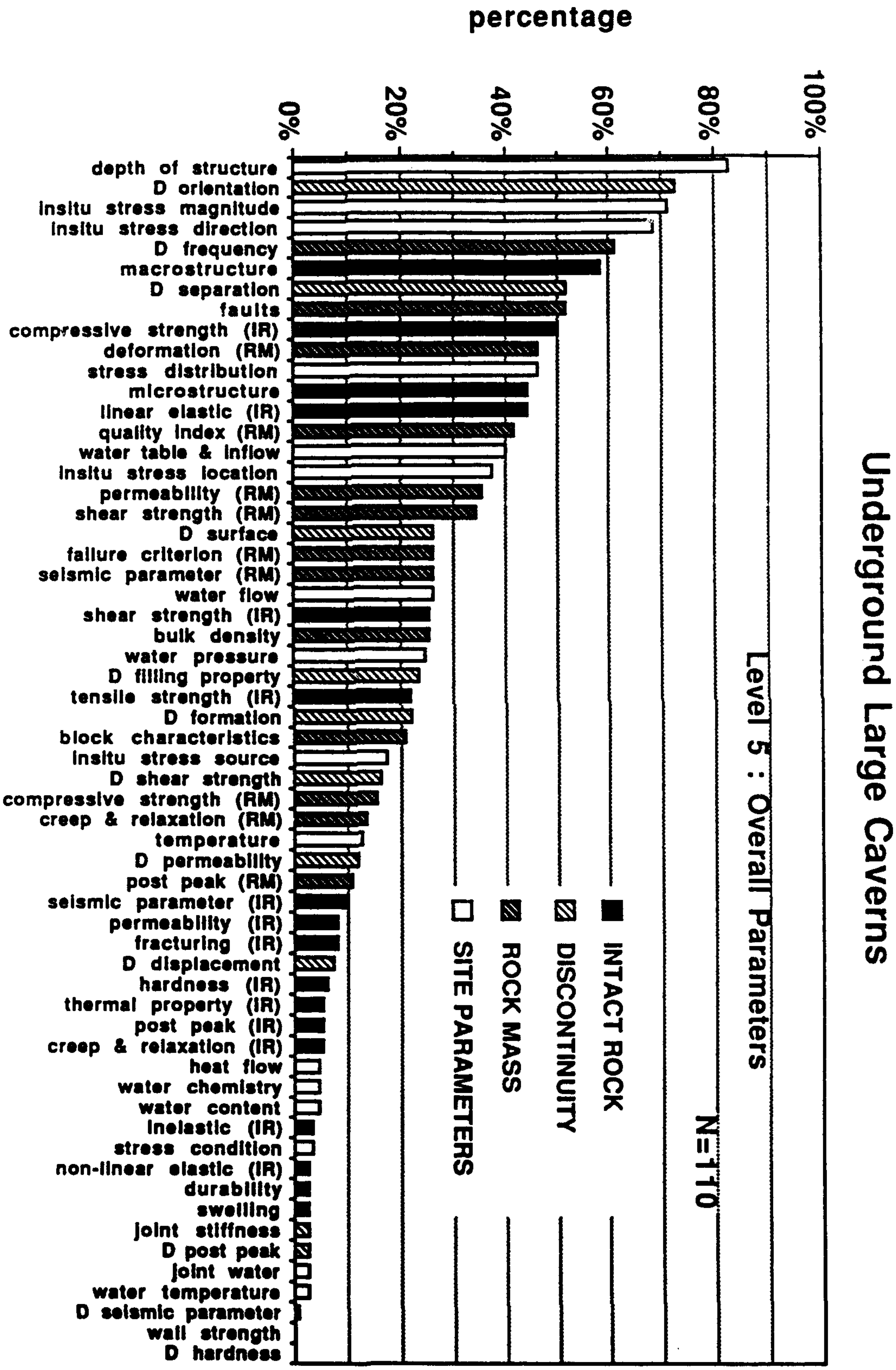


Figure 5. Histogram showing frequency of study of Level 5 parameters in Level 4 groups

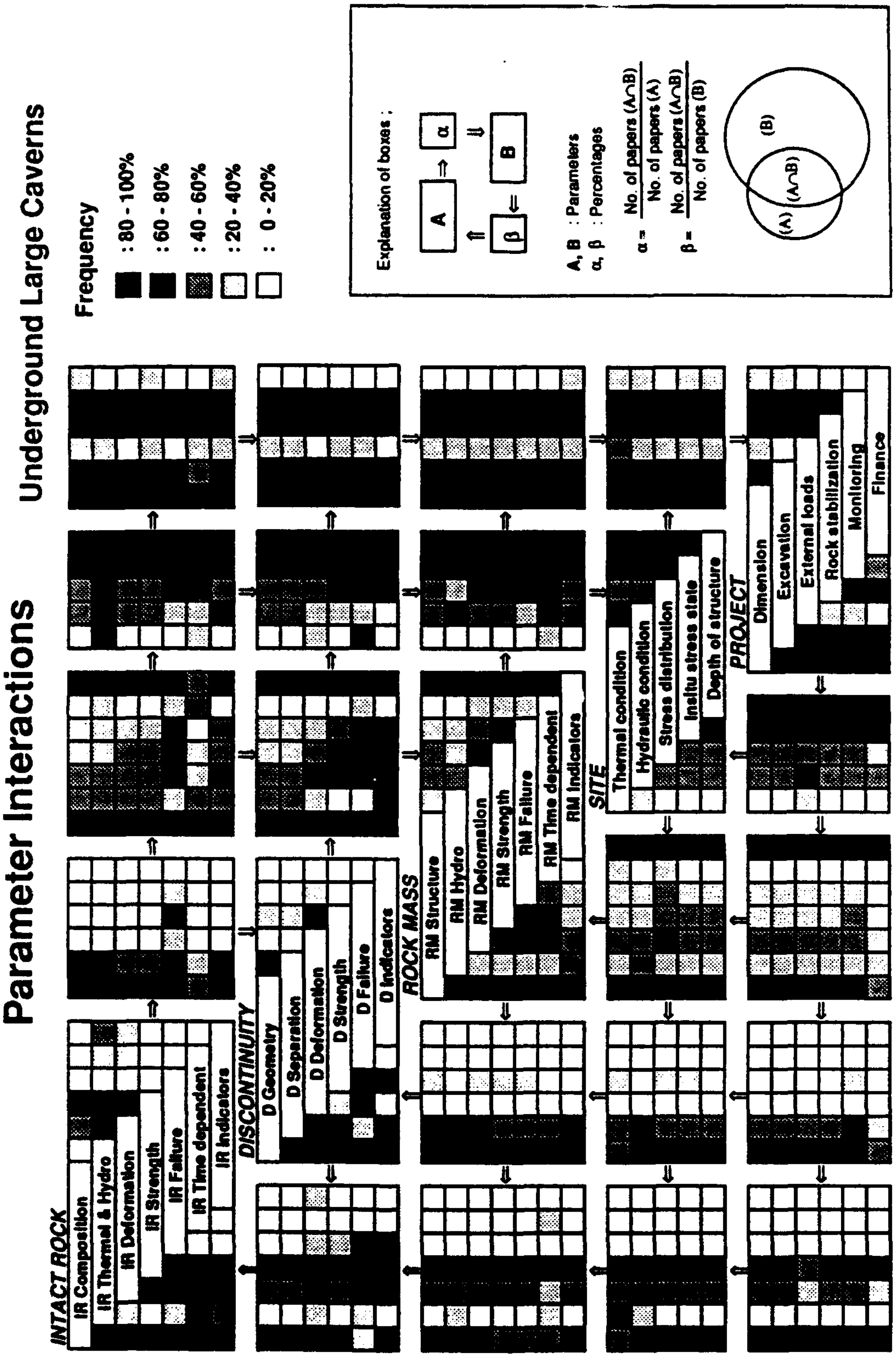


Figure 6. Large matrix of parameter interactions with 31 Level 4 parameters as leading diagonal terms.

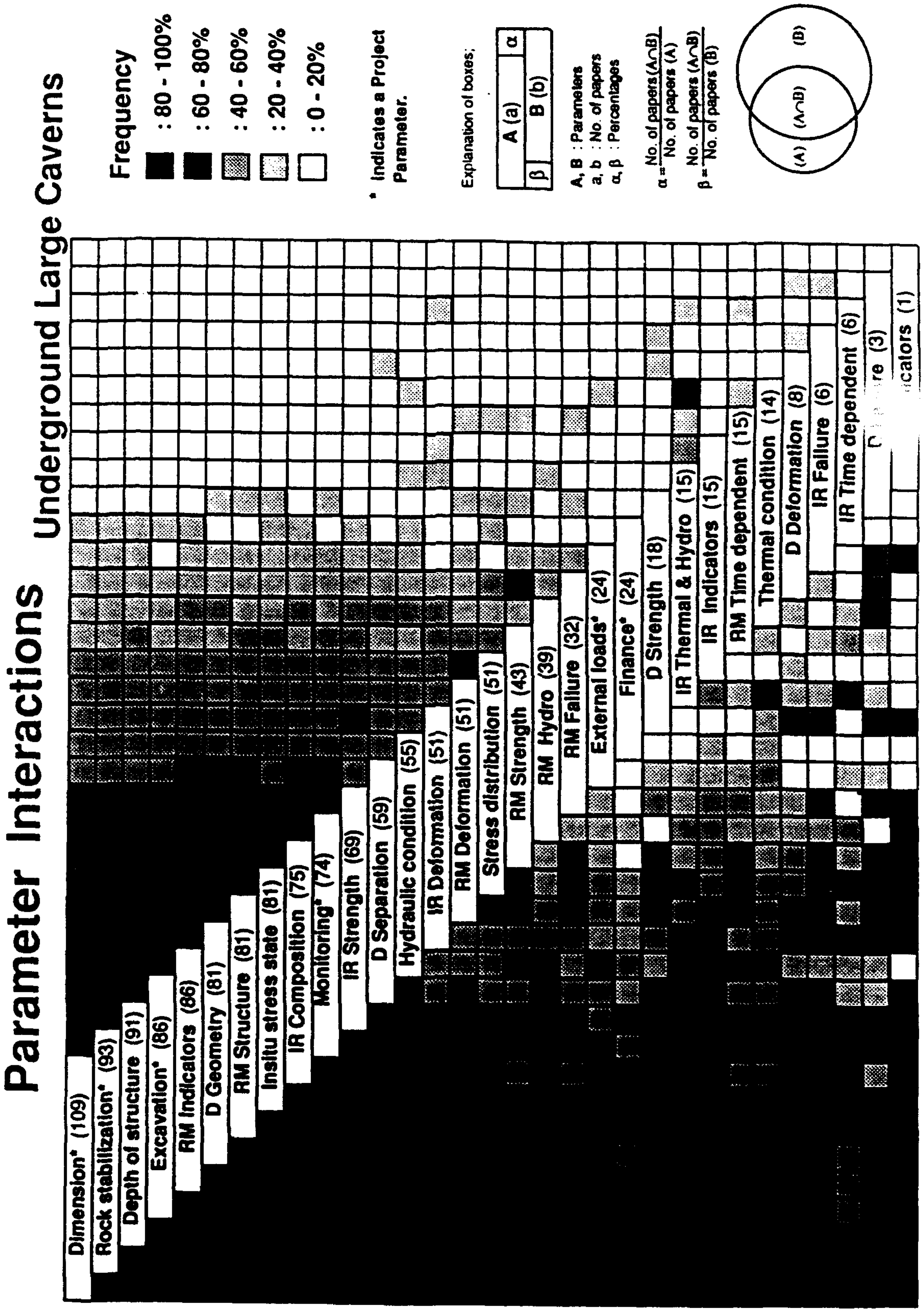


Figure 7. Large matrix of parameter interactions with 31 Level 4 parameters, ordered according to their priority, as leading digonal terms .

It is at this point that the proposed research will start, with improvement of the rock parameter flow chart, comparison of the three Level 1 approaches, how the priority changes with the project, and the superimposition of the design procedure on this technique. It will also be necessary to explore the link with set theory (as is evident by the small diagram at the bottom right of Fig. 7) and to use the more modern object-oriented computing techniques to 'control' the information.

This will lead to a methodology for rock engineering design. This research project is focussed on the methodology itself. Once this has been successfully developed, it is a separate exercise to develop the technique for any specific subject, such as radioactive waste disposal, dam foundations, tunnels, caverns, etc.

The work for the Contract commenced on 1 January 1991 and followed the program of work as specified in the Contract. Details will be found in Section 2.

2. ORGANIZATION OF RESEARCH EFFORT

The research effort was led by Professor J A Hudson, under whose guidance many of the postgraduate students in the Rock Engineering Group at Imperial College, London, UK contributed to the overall results.

In particular, the majority of the work was carried out by a number of students studying for their Doctorate degree and who were directly supported by Bursaries awarded via the provisions of this Contract, DAJA45-91-C-0008. These students are listed later.

In addition to the usual student/supervisor interactions between Professor Hudson and the Doctoral students, the work was progressed at a number of intensive Study Workshops during which a particular topic was presented, analyzed and discussed. These Workshops were found to be an exceptionally good method for consolidating our ideas and always led to a significant advance in our understanding of the Systems approach and new ways forward.

The Workshops usually lasted 2-3 days and were held in isolated locations so that no day-to-day interruptions would break up the flow of ideas. Small bed and breakfast establishments were ideal. Some Workshops involved only the bursaried students but frequently other students who were also involved in the Rock Engineering Group's overall thrust on the Systems approach were included. These were the students who received indirect support through the Contract. A total of 13 Workshops, funded by Rock Engineering Consultants, took place during the contract.

Research Objectives and Program of Work

The research program was organized in such a way that the Tasks specified in the Contract would be addressed and the various Milestones achieved. The Tasks and Milestones as stated in the Contract are summarized below.

Scope of Research

TASKS:

1. To crystallize the flow chart(s) for the "Rock Engineering Mechanism Information Technology" (REMIT) system development.
   a) Improve the existing flow chart, especially the levels
   b) Modify the flow chart to include rock mechanisms as well as properties,
   c) Consider the parallel or superimposed design flow chart on how one finds the optimal path through the information.

2. To explore the link with set theory and matrix theory to improve and be able to interpret the types of presentation.

3. To consider the use of object-oriented programming as a better way of hierarchical storage and manipulation of the data so that it can easily be grouped according to any algorithm arising from the flow charts.

4. To compare the parameter prioritization from the literature with current practice and also suggested practice as inferred from analysis techniques.

5. To suggest a practical rock engineering design methodology which utilizes the results of the previous tasks thus leading to improved engineering construction design, analysis, construction and monitoring procedures.

Objectives

Develop a procedure to enable engineers and researchers to decide for any project the relevant rock properties and their priority, relevant boundary conditions, rock mechanics mechanisms that should be suited, the interaction between these, and hence the overall type and sequence of site investigation, analysis, design, construction and monitoring that should be conducted for optimal use of the resource available. The way in which this approach (tentatively called 'Rock Engineering Mechanisms Technology' with the acronym REMIT) can be developed is described in the proposal. [Included in outline form above]

The proposed program of work was designed to be completed in three years with the work divided as follows:

Starting Date: 1 January 1991

Jan 1991 - Jun 1991	TASK 1 – Further literature review and development of theflow charts, both infrastructural information and the design process.
Jul 1991 - Dec 1991	TASK 2 – Interpretation and development of the presentation and logic via set theory, matrix theory. and network theory,
Jan 1992 - Dec 1992	TASK 3 – Use of object-oriented programming to computerize the whole system as a coherent whole.
Jan 1993 - Dec 1993	TASK 4 – To develop a rock engineering design methodology, to test it on finished, current and proposed projects and to make final recommendations regarding its use.

The milestones associated with this program were:

MILESTONE 1:	START RESEARCH	(Jan 1991)
MILESTONE 2:	ESTABLISHMENT OF FLOWCHARTS	(Jun 1991)
MILESTONE 3:	LOGIC/PRESENTATION COMPLETED	(Dec 1991)
MILESTONE 4:	COMPUTERIZATION OF PROCESS	(Dec 1992)
MILESTONE 5:	RECOMMENDATION OF METHODOLOGY	(Dec 1993)
	SUBMISSION OF FINAL REPORT	(Feb 1994)

The work commenced on time and progress was smooth with all Tasks and Milestones being completed to schedule.

3. SUMMARY OF RESEARCH FINDINGS

The work conducted for the contract was to develop a design methodology for rock engineering using the "Rock Engineering Systems" (RES) approach. The idea of an interaction matrix (in which the primary variables pertinent to a particular objective are listed along the leading diagonal of a matrix and then the associated mechanisms linking the variables are identified in the appropriate off-diagonal locations) had already been proposed. The work was to extend this concept into a working methodology — which was successfully concluded.

We found that:

- It is crucial to identify the engineering objective; there is no absolute suite of rock engineering parameters that can be used in design because they will be dictated by the objective.

- The rock engineering parameters or variables that are listed along the leading diagonal in the interaction matrix must be one of two types (which cannot be mixed); they must either be the usual engineering parameters such as rock strength, discontinuity geometry, water flow, construction, etc.; or be fundamental physical variables which can be explicitly linked through equations in the off-diagonal terms.

- The interaction matrix does, indeed, provide an excellent tool for identifying all the mechanisms: in the general engineering context with the engineering variables, more fundamentally with the physical variables, and at the two main sites where the methodology was field tested.

- The method of coding the interaction matrix to establish the significance of all the interactions for design was improved.

- There is a strong relation between the interaction matrix and graph theory. We anticipate that, in the future, this will lead to the Fully-Coupled Model (FCM) where the consequences of all variables being potentially connected to all other variables can be modelled and assessed explicitly.

- The computerization of the methodology that was appropriate and possible within the resource limitations of the contract was promising. We anticipate that future work will enable the methodolgy to be operated with full multi-media capability and with the decision support procedures already established.

- The methodology is ideally suited to incorporation of uncertainty (whether by Monte Carlo or fuzzy techniques) and to risk assessment; preliminary work on this subject was completed.

- Other research associated with the contract indicated that neural networks are likely to be the best computer tool for enhancing the RES design methodology even further.

4. PERSONNEL INVOLVED AND DEGREES OBTAINED

During the course of the contract a number of personnel from Imperial College were supported, in whole or in part, to take part in the research work. These are listed below. The first four named were the major participants and have (or will shortly) produced Doctoral theses on aspects of the Systems methodology. The remainder took part in various study workshops and thus contributed to the development of ideas. The two recipients of MSc degrees wrote their dissertations incorporating rock engineering systems ideas.

Kemal Gokay	PhD	March 1993
Peter Arnold	PhD	July 1993
Dean Millar	PhD	Candidate - expected May 1994
Jiao Yong	PhD	Candidate - expected December 1994
J Raimundo Almenara Chau	PhD	April 1992
Branko Vukadinovic		
Doug Spencer		
John Harrison		
Daria Mazzacola	MSc	September 1992
Walkeria Vinueza	MSc	September 1992
Alison Ord		

5. PUBLICATIONS ARISING FROM RESEARCH EFFORT

The following relevant publications were produced during the course of the Contract, either directly by the bursaried students or indirectly as a result of the group's effort.

1. Hudson J. A. Atlas of rock engineering mechanisms: Underground excavations. *Int. J. Rock Mech. Min. Sci*, 28, 523-526, (1991).

2. Hudson J. A., Arnold P. N. and Tamai A. Rock engineering mechanisms information technology (REMIT): Part I-The basic method; Part II- Illustrative case examples. *Proc. ISRM Int. Congress on Rock Mechanics*, Aachen, 1113-1119, (1991).

3. Hudson J.A. Atlas of rock engineering mechanisms. Part 2—Slopes. *Int. J Rock. Mech. Min. Sci.*,29, 2, 157-159, (1992).

4. Hudson J. A. and Harrison J. P. A new approach to studying complete rock engineering problems. *Quart. J. of Engin. Geology*. 25, 93-105, (1992).

5. Nathanail C. P, Earle D. A. and Hudson J. A. Stability hazard indicator system for slope failure in heterogeneous strata. Hudson J. A. (Ed.) *Rock Characterization* , Proceedings of the EUROCK '92 Symposium, Chester, UK, 14-17 Sept, 111-116, (1992).

6. Millar D. L. and Hudson J. A. Rock engineering system performance monitoring using neural networks. *Proc. of the Conference 'Artificial Intelligence in the Minerals Sector'*, University of Nottingham, Institution of Mining & Metallurgy, April, (1993).

7. Gokay M.K. and Hudson J. A. Recognition of excavation failure conditions by using knowledge-bases. Proc. *Int. Symposium on Assessment and Prevention of Failure of Phenomena in Rock Engineering*, Istanbul, Turkey, (Ed. Pasamehmetoglu et al) p. 785-789 (1993)

8. Hudson J. A. Rock Engineering Systems (Invited Keynote Address) *Proceedings of the 34th US Rock Mechanics Symposium*, University of Wisconsin-Madison, (Ed. B. C. Haimson), p. 261-270 (1993)

9. Hudson J. A. and Hudson J. L. Establishing potential behavioural modes of rock engineering systems by computer simulation of interaction matrix energy flux. *Int. J. Rock Mech. Min. Sci.*, 30, 4, 457-468 (1993)

10. Hudson J. A. Rock properties and testing methods. In *Comprehensive Rock Engineering*, J. A. Hudson (Ed.) Pergamon Press, Oxford. Chpt 1, Vol. 3, 1-35, (1993).

11. Hudson J. A. The construction process. In *Comprehensive Rock Engineering*, J. A. Hudson (Ed.) Pergamon Press, Oxford. Chpt 1, Vol. 4, 1-27, (1993).

12. Mazzoccola D. F. and Hudson J. A. A comprehensive method of rock mass characterisation for indicating slope instability. *Quart. J. Eng. Geol.* (in press 1993).

13. Hudson J. A., Sheng J. and Arnold P. N. Rock engineering risk assessment through critical mechanism and parameter evaluation. *Geotechnical Risk - identification, evaluation and solutions*, 6th Australian - NZ Conference on Geomechanics, Christchurch, 442-447 (1992).

14. Gokay M. K and Hudson J. A. Developing a knowledge-based decision support system for rock mechanics application. *Transfer Report*, Imperial College, London.

6. DOCTORAL THESES PRODUCED BY INVOLVED PERSONNEL

During the course of the contract the research work for four Doctoral theses on Rock Engineering Systems was completed. Two of these have been submitted and the Doctorates awarded. The other two theses, by the two remaining bursaried students, are in the final stages of writing. The titles and a brief abstract are listed below. Extracts from two of the completed theses are presented in Appendix A and Appendix B to provide an idea of the areas of investigation and the outcome of the work. Complete copies of the theses can be made available if required.

1. "Developing Computer Methodologies for Rock Engineering Decisions".
M K Gokay, March 1993, p. 396.

As rock engineering problems become more complicated, it is essential to be able to handle all the knowledge requirements at all stages and scales within the problem. The work provides a complete review of the approaches that are possible. Specific programs were written for storing, presenting, and manipulating information in the rock mass classification context, and in connection with the new rock engineering systems approach.

2. "The Development of a Rock Engineering Systems Methodology".
P N Arnold, July 1993, p. 377.

This is the first PhD on rock engineering systems — a methodology developed to enable all relevant parameters and mechanisms to be included in the rock engineering design. The report contains extensive discussions of all the factors, from an initial review of current practice and parameters used right through to the systems understanding of the total construction process. All the aspects of rock mechanics and rock engineering can be integrated with this methodolgy.

3. "Neural Processing in Rock Engineering Systems".
D L Millar, Expected May 1994.

The relatively new techniques of neural processing are applied generally to rock engineering systems and specifically to to the subjects of modelling stress-strain behaviour of rock, assisting in computer-aided recognition of discontinuities, modelling rock mass behaviour and rock mass characterization. Neural networks are used to assist in the 'cognition' of rock parameters and mechanisms. Cellular automata for simulating rock behaviour are included.

4. "Formalizing the Systems Approach to Rock Engineering".
Jiao Yong, Expected December 1994.

The interaction matrix enables the interactions between all the relevant parameters in a rock engineering problem to be listed out. These interactions can be quantified and mechanism pathways established by considering the interaction matrix as a network, and analyzing all the pathways using graph theory. This leads to the development of the 'fully-coupled model, described here both mathematically and as applied to case examples.

7. DISSEMINATION OF SYSTEMS IDEAS

As the work progressed further opportunities arose for the Principal Investigator, Professor Hudson, to publicise the ideas through a number of invited lectures and courses. These are listed below.

Invited Lectures

— Keynote lecture at 34th US Symposium on Rock Mechanics, Madison, June 1993.

Rock Engineering Systems Courses

— Chester, UK, in association with EUROCK '92, September 1992. 1.5 days.

— Stockholm, Sweden, at the Geotechnical Department of The Royal Institute of Technology, May 1993. 5 days.

— Singapore, at the Nanyang Technological Institute. December 1993. 2 days.

— Hong Kong, at the Hong Kong Polytechnic, December 1993. 2 days.

— Futher lectures and courses are scheduled to take place after the end of the contract period, including the short course:

—"Rock Engineering Systems: Practical Methodology" to be held in association with NARMS at Austin, Texas, USA, 31 May 1994.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

1. All the work items in the contract were completed and the development of a design methodology for rock engineering was successfully achieved. The main findings have already been individually listed in Section 3 of this report.

2. The resources provided by the contract resulted directly in two PhD theses (see Appendices A & B), directly in two MSc theses, and indirectly in two further PhD theses. Thus, not only was the contract work itself successful but it also provided significant benefit to the academic community.

3. The work has indicated that further research on the following topics would be very productive:

a) The specification of the objectives of a civil engineering project involving construction in or on rock masses. There is no current methodology for doing this.

b) The specification of the information requirements for the design of a rock engineering project. There is no current methodology for this either, yet the Rock Engineering Systems approach is ideally structured to provide this capability.

c) The specification of uncertainty in rock engineering information. We know that there will always be incomplete information yet we have no formal methodology for this.

d) Development of the Fully-Coupled Model based on the work conducted for the contract. The work would be to extend the conceptual base to the explicit mathematical linking of the variables in any scheme. In this way, the effects of uncertainties, certain values of the geotechnical parameters, particular engineering activities, etc., could all be evaluated.

e) Finally, this would lead to a capability for technical auditing of any rock. Have all the variables and mechanisms been taken into account? Is enough information available? Can any of the mechanisms run out of control as a result of engineering? Etc. There is no current technique available for this type of technical auditing, yet it will be crucial in the years ahead as projects become more complicated and more linked to environmental concerns.

APPENDIX A

OUTLINE OF DOCTORAL THESIS

"THE DEVELOPMENT OF A ROCK ENGINEERING SYSTEMS METHODOLOGY"

THE DEVELOPMENT OF A ROCK ENGINEERING SYSTEMS METHODOLOGY

A Thesis
submitted to the University of London
(Imperial College of Science, Technology & Medicine)

by

Peter Nicholas Arnold

In fulfilment of the requirements
for the degree of
Doctor of Philosophy

JUNE 1993

ABSTRACT

In any rock engineering problem there are a multitude of rock properties that could be measured. Similarly there are a multitude of rock mechanics mechanisms that can be invoked, and the structure can be designed to defend against many types of potential collapse mechanisms. Furthermore, all these properties and mechanisms influence one another to a greater and lesser extent. One is therefore faced with making a decision in an increasingly complex environment on how to proceed from the original rock engineering requirement.

The aim of this thesis is to present an initial framework in which engineering properties, interactions and mechanisms can be structured and studied, thus providing a means for identifying the pertinent factors for any rock engineering project and engineering objective.

The development of the methodology is commenced by, categorising rock, site and engineering parameters into a hierarchical framework, identifying the parameter priority for different engineering objectives, and structuring rock engineering mechanisms by networks of multiple parameter interactions. The methodology is formalised using the rock engineering interaction matrix, where parameters form the leading diagonal of the matrix, binary interactions are located in the off-diagonal boxes and mechanisms are considered via interaction matrix pathways. Coding of the binary interactions allows the interaction intensity and dominance of parameters to be identified in Cause and Effect space. The system is refined by considering conventional systems concepts. The implementation of the methodology within the phases of the rock engineering process is proposed.

The methodology is applied to two rock engineering projects. The first case study, an underground research facility, uses the overall strategy for structuring information and processes into a coherent system. The second case study applies the tactics to develop a classification system, for a sequence of rock slopes, tailored explicitly to the rock, site and engineering situation.

The methodology has ramifications for data collection, model development and for directing each stage in the rock engineering process.

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CHAPTER 1

Introduction

1.1 The Rock Engineering Problem

Figure 1.1: The consequence of a landslide at Mount Rabbat, Spain.

Figure 1.1 above, shows the devastating effect of a landslide on one of the cuttings along the A-7 Mediterranean Autopiste at Mount Rabbat in Spain. The rock cutting, that was one of the smaller excavations made along this route, maintained its stability as

required, despite the failure of the whole hill side. Many factors could have contributed to this failure.

The stability of the rock cutting may have been the focus of attention during design without considering the wider implications of this cutting on the rest of the environment. A weak marl layer on which shearing occurred may not have been identified during ground investigations, or if it was the importance of this feature may not been acknowledged. It is also possible that the cutting had little influence on the landslide, which may have occurred anyway some time later. One also needs to consider whether such an instability is acceptable in view of the time and financial constraints imposed on the whole construction project.

This example highlights some of the problems that face rock engineering today. Not only are there difficulties in obtaining relevant and representative data on the rock mass conditions but there are also uncertainties into how the rock mass will behave before, during and after construction to the satisfaction of the project objectives. There is therefore a need for an approach that will direct the practitioners of rock engineering towards the most appropriate classification and modelling technique for the circumstances that are encountered. The solution to any rock engineering problem is never merely technological, it requires the information requirements, analysis techniques and the engineering implementation to be directed, optimized and planned, which can only be achieved by structuring the whole rock engineering process into a coherent framework.

This thesis is concerned with the development of a methodology to direct the rock engineering process. Before the aims and contents this thesis are discussed, the following section will highlight some of the attributes, dilemmas and challenges that face us today within this subject of rock engineering.

The Rock Property Problem

Rock masses, have been formed by geological processes over millions of years resulting

in a highly variable fractured medium. The properties and behaviour of rock masses vary at different scales and through time. Unlike other engineering disciplines where the engineer can fabricate the material properties for the structure at hand, rock engineers have to investigate the properties of the material in which engineering is to be performed. Only a fraction of the rock mass will ever be investigated and thus there is always an inherent uncertainty in defining accurate parameter values and establishing that any major geological features have not been missed. Not only are there difficulties in obtaining representative parameter values but there are also difficulties in assessing the parameters at a scale commensurate with the domain of engineering influence. Many recommendations have been provided on how to measure rock properties but there are fewer guidelines on which parameters should be obtained for specific engineering objectives and which mechanisms should be defended against. The mode of behaviour of a rock mass when excavated may depend upon a number or a few key parameters, as with the failure shown in Figure 1.1. However, there are a multitude of rock properties which can be measured and similarly a multitude of mechanisms which can occur but there is currently no list all of rock properties and similarly no list of all the mechanisms that can be invoked.

The Rock Mechanics Design Problem

Although rock engineering structures have been constructed for over thousands of years, a scientific study into rock mechanics phenomena has only been established in its own right in the last thirty years or so. This has led to the development of many theories and criteria for describing the way rock masses behave. The methods of analysis developed from these theories have provided a more scientific understanding to rock mass behaviour. Many of these theories have been taken from other engineering disciplines. Numerical methods for stress analysis have now become widely available and are particularly useful for modelling complex engineering structures and shapes. However these techniques can only model certain responses requiring simplification of their constitutive parts for mathematical convergence. Also, they have outpaced our ability to obtain the necessary input data. Given the near infinite complexity of rock masses, some design techniques have been developed to bypass any detailed analysis preferring to base

the design on observational or empirical approaches. Observation design methods, such as the New Austrian Tunnelling Method (NATM), rely principally on the measurement of displacements during construction to evaluate support and stabilization measures. Rock mass classification systems embody the empirical approach to rock engineering design and use a few key parameters to determine stabilization guidelines. None of these design techniques are directly usable by practitioners as they need to be tailored to the geological situation, engineering objectives and project circumstances.

There is a plethora of rock mechanics and rock engineering information available for aiding the design of engineering structures, but the optimal implementation of rock mechanics theory to rock engineering practice still tends to remain in the domain of the expert. One reason is that information sources are not always structured in an accessible manner for direct use by clients, consultants and engineers. Another reason is that engineering judgement based on precedent experience forms a major part in present day rock engineering.

Rock Engineering Requirements

The demands on rock engineering are increasing for the purposes of mineral extraction, energy and civil structures. Many of the new rock structures being proposed are novel and without precedent, for example, the storage of high level nuclear waste in underground repositories. Others need to be constructed within stiff environmental and safety constraints and within tighter financial budgets without the spiralling and escalating costs so frequent in many of today's rock engineering projects. The desire to optimize any part of the rock engineering will be restricted by the constraints imposed. Constraints cover a wide and diverse range cf criteria and can include such as factors as location, shape and dimension of the engineering structure, financial limits, contractual arrangements, time limits for each stage of the works, expertise and personnel available and possibly political and ethical considerations. The objectives and constraints essentially constitute the degree of flexibility in which the project can operate and can be considered to be the project management boundary conditions.

Despite the wide variety of rock engineering projects, the type of engineering structures are limited. In Table 1.1, a list of the principal rock engineering projects and engineering structures is presented. Given the near infinite use of structures for civil purposes and mining in rock these are not included individually.

Each of these engineering projects will have their own specific engineering objectives and in any project, there will be numerous sub-objectives and goals relating to specific tasks of the works. The objectives for constructing a road tunnel are fundamentally different from those associated with underground nuclear waste disposal although the engineering structures may be similar. Consequently, the focus of the mechanisms that must be defended against are fundamentally different. This has ramifications for the direction of each stage in the rock engineering process.

Table 1.1: Typical rock engineering structures and purposes

PURPOSE	ENGINEERING STRUCTURE (Temporary / Permanent)	COMPOUND STRUCTURES
Hydro-electric Power	Tunnel	Intersection
Radioactive Waste Disposal	Cavern/ Chamber	Portal
Geothermal Energy	Borehole	Draw Point
Petroleum/Gas Extraction	Shaft	
Petroleum/Gas Storage	Slope	
Civil Structures	Foundation	
Open Cast Mining	Pillar	
Underground Mining	Stope	

In rock engineering four groups of activities can be performed: exploration, excavation, stabilization and monitoring. Within this group there are a number of methods and techniques that can be performed as shown in Table 1.2. Each technique has its own attributes that will be optimal for certain circumstances. The selection and application of each technique will have its own specific objectives and its implementation needs to be planned. Exploration is directed towards data collection, either to establish the initial and boundary, rock and site conditions before excavation or to understand the rock mass response to a prototype engineering structure. Excavation and stabilization directly interact with the rock mass to alter the rock structure to the construction requirements. Monitoring is essentially a passive activity to evaluate the actual rock mass response to

construction or post construction effects.

Table 1.2: Some methods within four rock engineering activities

EXPLORATION	EXCAVATION	STABILIZATION	MONITORING
Desk Study Surface Investigation - field measurements - *in situ* testing Drilling Investigation Exploratory Adits Geophysical Methods Laboratory Testing	Blasting - pre-split - bulk - smooth Cutting - partial face - full face TBM Ripping Impact - pneumatic breakers Abrasion - water jets	Reinforcement - rock bolts - cables - anchors Support - steel arches - shotcrete - concrete lining - backfill Ground Alteration - grouting - freezing	Parameter Measurements - in situ stress - displacements Performance Evaluation - NATM Environmental Impact - vibrations - surface subsidence - seismic Post Construction Evaluation - convergence

1.2 The Concept of a Rock Engineering Methodology

Rock engineering is a system that commences typically with a feasibility study through to site investigation, excavation, stabilization and monitoring. Each phase contributes to the knowledge base by providing information about the possible rock conditions, the actual rock conditions encountered and its behaviour when engineered. Also each phase has a degree of uncertainty associated with it. Each phase needs to be planned, implemented and evaluated so that the information obtained is relevant to the engineering situation and contributes towards a reduction in the uncertainty. In turn the information received needs to be analyzed to reduce the uncertainty for the following and subsequent phases of the rock engineering process. A prediction of the behaviour of the rock mass cannot be made unless the problem can be formulated in mechanical terms. There therefore needs to be rational procedure in which rock engineering can be implemented not just in a satisfactory way but an optimal way. This is the role of a rock engineering methodology.

A methodology can be considered to be a structured approach that allows an evaluation of a variety of methods that can address a problem. Following a methodology will not necessarily result in a solution. A method, in contrast, is an orderly way of proceeding which if followed results in a solution. It is considered that due to the multifarious factors which influence a rock engineering problem together with our current state of understanding on the subject, there will not be a generic method for all rock engineering. However there is the potential for developing a rock engineering design methodology to direct attention and to provide a framework in which rock mechanics knowledge can be tailored to the rock engineering circumstances.

Methodologies have been successfully developed for other engineering disciplines that enable the generation, development and evaluation of possible design solutions. These methodologies for traditional engineering disciplines provide a structure and a science to design and problem solving. However, given the fundamental difference between traditional engineering disciplines, such as structural and mechanical, and ground engineering these approaches are not directly applicable.

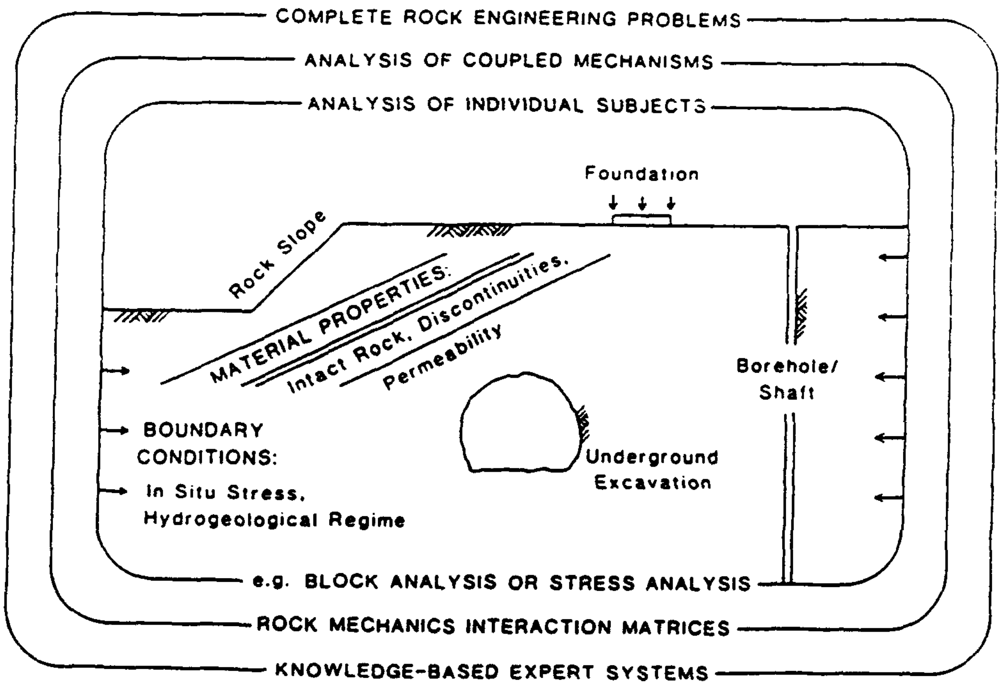


Figure 1. 2: The context of rock engineering to the rock mechanics analysis (Hudson 1989)

To provide an introduction to the some of the factors that constitute the approach to rock engineering and rock mechanics, Hudson (1989) presented a broad view of how these topics are structured. This is shown in Figure 1.2 and comprises breaking down the problem from the global to the specific. Rock mechanics is the study of the response of rock to an applied disturbance. In rock engineering this involves understanding the material properties and the pre-existing boundary conditions as well as the nature of the disturbance itself (Hudson 1989).

The overall design process has been structured by Bieniawski (1984) as comprising an iterative cycle as shown in Figure 1.3. This structure is initiated by objectives and constraints to direct the exploration programme. The information obtained is utilized by analysis and synthesis to develop a coherent model of the rock, site and engineering conditions. Evaluation and optimization of the design analysis lead to its implementation via communication in some standard and unambiguous form. Bieniawski comments that this cycle is directed counter clockwise to signify the challenge to design engineering who have to move 'against the tide' of prejudice which views design studies as a 'soft' subject for engineering.

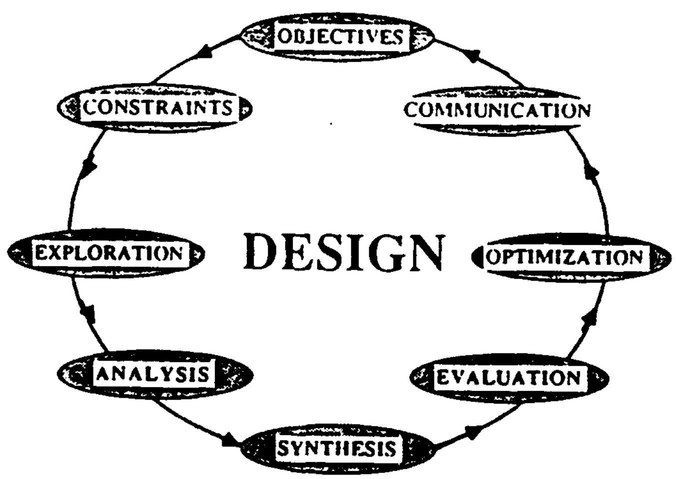


Figure 1.3: The design cycle for rock engineering (Bieniawski 1984)

The above introduction shows the diversity in the information needs, rock engineering activities, construction projects and their objectives. This along with the diversity in

geological conditions require a systems that is robust but directs the user to their required objectives.

1.3: Structure and Content of this Thesis

This thesis is concerned with the development of a rock engineering systems methodology. The basis of the methodology is to provide a framework and a structure to the study of rock mechanics phenomena and rock engineering processes. The title of this thesis is directed towards studying: i) the rock engineering process as a system, made up of an number of parts organised within a structured framework and ii) structuring the rock engineering mechanisms from a systems perspective. The structure of the thesis is shown in Figure 1.4.

The thesis is divided into four parts:

Part 1: Background and Literature Review
Part 2: Developing the Methodology
Part 3: Implementing of the Methodology
Part 4: Refining the Methodology

Part 1. Literature Review

The first three chapters of this thesis contain the statements on the background to the rock engineering problem and a literature review of existing methods and methodologies used in rock engineering.

In Chapter 2, some existing methodologies which have been published for rock engineering and site investigations are highlighted. These tend to illustrate the framework in which design and engineering activities take place. Several existing techniques for aiding site investigation planning are also described. The limitations in the application of these techniques to the more newer uses in rock are considered along with the future demands on rock engineering. The existing methodologies place little emphasis on how the objectives of the engineering relate to the relevant parameters and

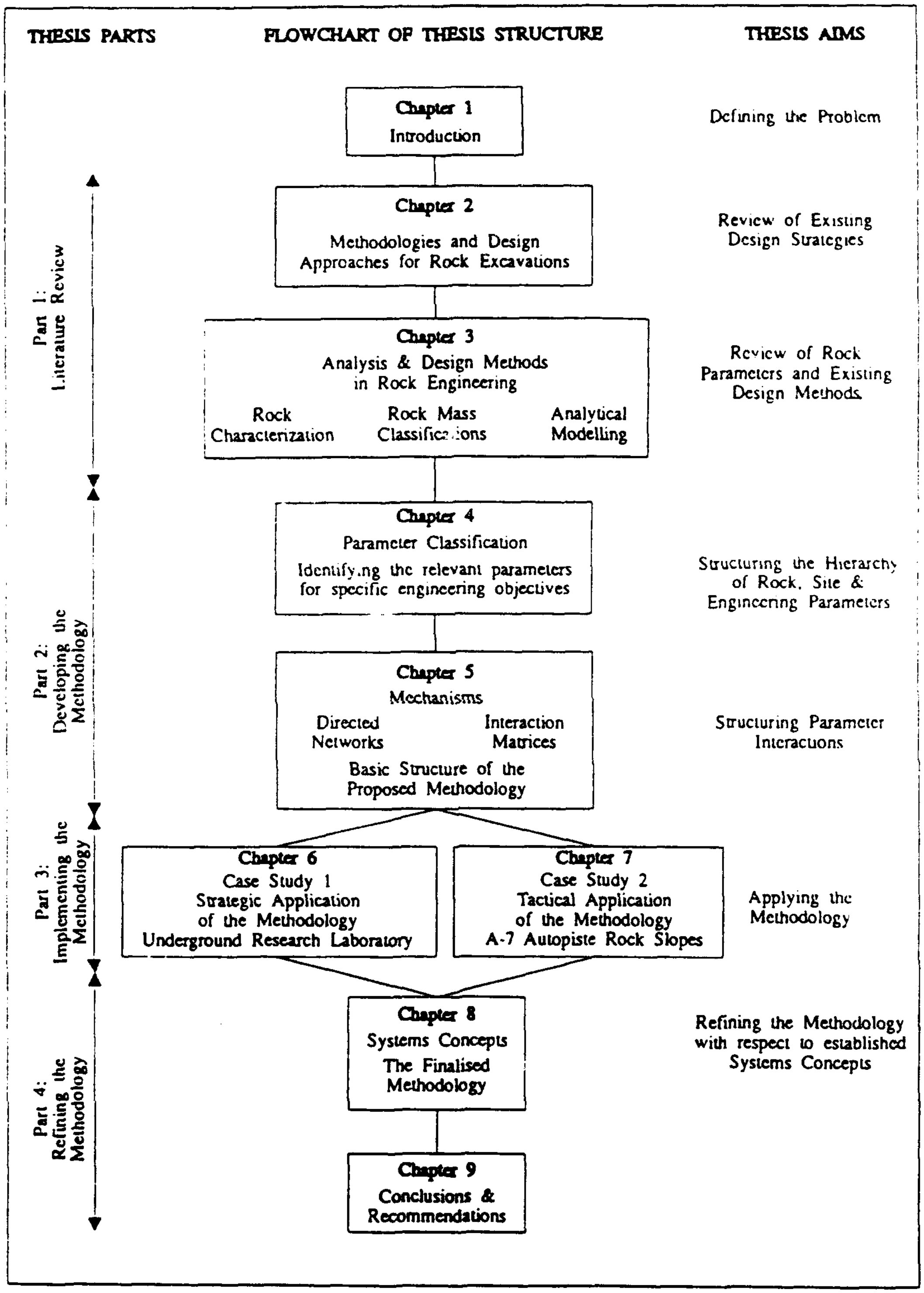


Figure 1.4: Thesis Structure

mechanisms and provide no structure in which the parameter interactions can be studied.

Chapter 3 provides an overview of the techniques and methods used in rock engineering design, with emphasis on the suitability of these techniques to different geological and engineering situations, and the input parameters used in these methods. Initial consideration is given to the type of parameters that can be obtained from rock masses. This is introduced by considering the behaviour of the rock mass with respect to the problem domain. From this perspective an assessment of the rock properties available from field measurements, laboratory and *in situ* testing is made for continuum and discontinuum modes of behaviour.

The design techniques in rock engineering utilize the rock parameters for either an empirical, numerical modelling or monitoring approach. Engineering rock mass classifications embody the heart of the empirical approach and are discussed in detail with respect to their components, structure and development. Many of their attributes have implications for the study of parameter interactions and coding methods used later in Chapter 7. Numerical modelling approaches to design are discussed in similar terms and a more detailed inspection of the parameters used within a numerical modelling code, FLAC, is presented.

Although these techniques and methods of analysis have a role within the design process, there is currently no direct way to determine their suitability for a particular engineering project and site condition. The geotechnical model needs to be commensurate to the rock, site and engineering situation. The model also needs to be developed to satisfy the engineering objectives. It is suggested that the types of parameters used by these different methods are at different resolutions. This introduces the concepts concerning parameter hierarchy and questions the form and type of parameters required for all aspects of the engineering design process. The need for a new approach and perspective is advocated.

Part 2, Developing the Methodology

This section commences the authors research into the development of the new approach. Chapter 4 commences with a classification of all known rock, site and project

parameters. The developed hierarchy of some 200 rock engineering parameters, is used to study the relevant parameters for specific rock engineering projects including pressure tunnels. This analysis of the literature, as representative of precedent practice, identifies the base line parameters for these rock engineering projects. Many of these parameters are different from those used in rock mass classifications and numerical analysis, justifying the fact that the parameters should be commensurate with the engineering objectives. At the end of this section, the levels of the preliminary system are presented. Recognition of the need to study the mechanisms created by the parameter interactions rather than the parameters in isolation forms the subject for the next chapter.

In Chapter 5, a generic approach to formalize a structure of rock engineering mechanisms from rock, site and engineering parameters is generated. Directed networks are produced to show the sequence of interactions between the parameters for certain instability scenarios (pressure tunnels leakage modes and block falls). The directed networks produced illustrate a number of important concepts regarding parameter interactions and instability mechanisms, namely the concepts of threshold values and stores, feedback mechanisms and the necessary criteria for the mechanisms to function. The networks, however, do not provide a generic approach for structuring all potential mechanisms and interactions.

A more systematic approach is provided with the use of interaction matrices. This technique, that places rock, site and engineering parameters along the leading diagonal of the matrix, provides a framework for the study the interactions in the off-diagonal interaction matrix boxes. Coding techniques applied to represent the interaction intensity of each off-diagonal box allow analysis of the whole rock system. This is performed by considering the sum of the coding in the matrix rows and columns for each parameter. When plotted in Cause and Effect space, the parameter intensity and dominance can be established, which can be interpreted in terms of the engineering objectives. The theory developed with this work, as published by Hudson (1992), is introduced and the concepts applied to the pressure tunnel case example.

Instability mechanisms are considered as pathways through the matrix. Although the coding techniques employed so far, are unsuitable for an objective evaluation of

potential instabilty mechanisms, a subjective assessment of how the pathways can be represented in the matrix is presented.

The structure of the system so far developed, incorporating the link between project objectives, mechanisms and parameters, is shown. The initial structure of the methodology developed is implemented to two case studies in Part 3.

Part 3: Implementing the Methodology

In Part 3, to complement the generic system and methodology developed in the previous parts of this thesis, two case studies are used to demonstrate the strategic and tactical, application and implementation, of the approach.

In Chapter 6, a strategic example of the methodology is applied to several studies at the Underground Research Laboratory (URL) in Canada. The information obtained at the URL is used to develop a preliminary geological interaction matrix. This matrix is expanded to study the interactions for the design objectives of an experimental tunnel - the Mine-by Experiment. Both the effects of the rock and site parameters on the tunnel design and the construction effects on the rock and site parameters are interpreted in terms of the project objectives. Finally inferred matrix pathways are used to re-interpret a stress prediction programme, using the information obtained to structure the difficulties encountered in decoding stress measurement information.

In Chapter 7, the methodology is applied to a sequence of excavated rock slopes along the A-7 Mediterranean Autopiste in Spain. In this case study, the tactics of the methodology are used to identify the critical parameters and interactions for each rock slope. A characterization systems is tailored to the site circumstances and post-construction situation using the interaction matrix and Cause and Effect plot. The structure of the system developed is discussed in detail. Other subsidiary classification techniques are introduced including a synergy rating system and an equivalent Rock Mass Rating system. An attribute of the classification system developed is compared with the results of the traditional classification systems to rank the rock slope order. A critical review of the system employed and recommendations for its improvement are given at the end of this chapter.

Part 4: Refining the methodology

In Part 4, the methodology is refined further. Systems concepts are introduced to demonstrate that the concepts developed so far are in fact part of a much wider subject Consideration of the interaction matrix and the methodology developed are interpreted in system terms. Traditional general systems theory is discussed and its implications for rock engineering indicated. A systems perspective is incorporated into the methodology developed so far and the types of systems identified allow re-interpretation of the parameters and interactions in terms of morphological, cascading and process-response systems. Engineering control systems are interpreted from the matrix operations. This results in the foundations of a systematic approach and a completely new methodology to the study of rock mechanics and rock engineering phenomena.

Finally, the methodology is structured within the whole rock engineering design process. A suggestive strategy for implementing the methodology is given by considering four cycles of information, information interpretation and engineering implementation throughout the sequence of engineering activities and design considerations.

A summary of the authors contribution to this subject of rock engineering is given in the global conclusions in Chapter 9 of this thesis. The ramifications of the methodology are highlighted and recommendations for further work suggested.

CHAPTER 9

Conclusions and Recommendations for Further Work

9.1 Conclusions

The aim of this thesis was to develop the initial structure for a rock engineering methodology. It has been shown that the methodology requires the structuring of rock engineering mechanisms. This has been achieved by considering the parameters, their interactions and consideration of interaction pathways leading to mechanisms manifest in rock engineering situations. For the generic situation, the interaction matrix has provided the means in which to structure the parameter interactions. Rock mechanics mechanisms are derived from concurrent and consecutive pathways through the parameter interactions around the matrix.

The major part of this thesis concentrated on the rock engineering parameters and binary interactions produced by these parameters as a precursor to the determination of interaction pathways. As there are a multitude of rock engineering parameters that can be measured and similarly a multitude of mechanisms that can occur in any rock engineering situation, the methodology for specific rock engineering projects requires the selection of the pertinent factors to be assessed for their effect on the engineering objectives. An analytic modelling approach is advocated, where any problem is tackled initially and strategically from the top-down. This has introduced the concepts of parameter hierarchy as a method for breaking down the problem to the required level of resolution for the circumstances that are faced. At any level in the parameter hierarchy, parameter interactions can be studied by a synthetic approach. In this way the strategy is analytic but the tactics are synthetic. When the baseline parameters are established for a specific rock engineering objective, these form the fundamental model

components and the model can then be built up knowing that it has converged on the correct model for the engineering situation. The model has thus been tailored to the rock, site and engineering situation. Structuring the model has been considered in terms of different levels of complexity ranging from the morphological, cascading, process-response and control system concepts. System concepts have been applied throughout the development of the methodology and formalised in the last chapter in terms of traditional and general systems theory.

The methodology has been developed to direct each stage of the rock engineering process, that is the sequence of activities from project inception to post construction monitoring. Throughout the rock engineering process, information is obtained, processed, interpreted and analyzed leading to the implementation of some form of action (e.g. collect more data or construct the excavation). The methodology was applied to two fundamentally different projects at different stages in the rock engineering process. At the Underground Research Laboratory in Canada, a strategic application of the methodology provided a technique for structuring information and processes. In particular the effect of parameter interactions on parameter measurement was indicated. The tactics of the methodology were applied to a sequence of slopes along the A-7 Autopiste in Spain. This provided a technique for classifying rock masses based on correlations and mechanisms between parameters rather than considering parameters as independent components, as in the tradition classification systems. Accordingly, the classification demonstrated how the parameters and their couplings should be commensurate with the mechanistic situation, thus being a preliminary system model for more detailed and rigorous rock mechanics modelling.

9.2 Contribution made in this Thesis

In this section, the major contributions made by the author to the subject of rock mechanics and rock engineering, as presented in this thesis, are as follows:

1) Many books and papers has been published discussing the types of rock mass classifications and their relative merits. In this thesis the author has identified the

common structure, attributes and components of rock mass classification systems used for engineering purposes. Classifications must be based and directed to specific objectives so that they can be tailored to the rock, site and engineering situation that is faced. This is not always performed in practice. They must contain the parameters that have a bearing on and control the mechanisms that are to be defended against. As each project has its own objectives and particular circumstances there will not be one all embracing classification method. There is therefore a need for a classification methodology.

2) The author undertook a literature search to identify the most frequently mentioned parameters for hydro-electric unlined pressure tunnels in rock. This assessment of precedent practice parameters for these types of engineering structures identified the parameter ranking. A similarly study for other engineering projects indicated that the most frequently measured parameters are different, thus justifying the need for tailoring classification system parameters to the engineering objectives.

3) A comprehensive catalogue of rock engineering parameters is presented in a hierarchical structure. At the coarsest level, the parameters are grouped into the categories of rock, site and engineering. Further sub-division of the rock mass properties into physical, mechanical and non-mechanical attributes was shown. This was developed into a preliminary methodology. The methodology is entered from the project objectives to identify the mechanisms that are to be defended against. This is determined from precedent practice, existing practice (design guidelines) or suggested practice (expert evaluation). For suggested practice, each instability mechanism is assessed from the interactions between the parameters at increasing levels of resolution.

4) The directed networks for some simple instability mechanisms were developed to show that from a selected level of parameter resolution, a sequence of concurrent and consecutive interactions can be built up to represent instability scenarios. Of major importance in this work was the interpretation of the interactions and their connections in terms of thresholds, stores, time dependency (delay) and feedback - the foundations of systems theory. This work was re-interpreted using the

interaction matrix to provide a more generic approach allowing all interac within the system to be candidates.

5) The coding techniques presented in Chapter 5 of this thes[illegible] by Hudson (1992). The author advanced these principles to the st[illegible] mechanisms. By interpreting the parameter constellation i[illegible] Ca[illegible]se [illegible] and by considering the mechanisms that are to be defended against, identified the function of the parameters by virtue of their intensity and [illegible] This provided a means in which to suggest possible [illegible]gineering [illegible]lutions [illegible] altering suitable parameters. The influence of grouting the [illegible] inuit[illegible] was shown to be akin to the effective deletion of a parameter (d[illegible] ty [illegible]chanical properties) in Cause and Effect space. The improvements to al[illegible] other p[illegible]rameters, by reducing their intensity within the system was expounded. Accordingly, this provided a technique in which various engineering alternatives can be assessed.

6) The strategy of the methodology was applied to information obtained from the Underground Research Laboratory. From a simple 4 by 4 matrix, the off-diagonal interactions representative of the geological setting was presented. This is the first ever application of the matrix to an actual rock engineering situation. Accordingly, the technique was shown to not only provide a structuring of information but also provide a knowledge statement. Other leading diagonal terms can be added to the matrix (fundamentally different or by increasing parameter resolution) to allow a systematic evaluation of other potential interactions associated with radioactive waste disposal, for which there may be few current procedural guidelines within established practice.

The association between the row and column engineering interactions and the engineering objectives were retrospectively shown for the tunnel excavated for the Mine-by Experiment. In this case, the column interactions for engineering showed how the experiment was controlled. The row interactions for engineering showed how engineering instigated the objectives of the research.

A stress prediction programme undertaken to investigate a disparity between

predicted and measured stress variations within a rock volume was retrospectively interpreted via the interaction matrix. This showed a coherent structure to the investigation and provided a means in which interactions can be systematically eliminated as possible contributory factors affecting the cause of the disparity. The matrix indicates the perils of ignoring the system interactions. The determination of accurate parameter values require a thorough understanding of all the system interactions and potential pathways.

7) The tactical application of the methodology was demonstrated in the development and application of a rock mass classification system to a sequence of engineered rock slopes. The classification system was developed by taking into account the teractions between the parameters thereby incorporating mechanistic phenomena. spite having no empirical basis, the classification system developed has numerous vantages over existing classification systems, which are mentioned below:

i) The parameters selected were commensurate with limited time available for the field survey, thereby providing a rapid "first pass" analysis to identify parameters of detriment to slope stability. The parameters were also selected so that they have a direct bearing on the mechanisms of detriment to stability and the processes occuring in the study region.

ii) Ger c coding of the matrix produced a weighting for each interaction that formalised the regional mechanical setting. This established the *a priori* intensity of each interaction. The rating system for each parameter at each rock slope was determined by a *posteriori* evaluation of parameter variations across the slope sequence, producing a relative rating system. The product of the rating and weighting for each interaction determined the intensity of the interaction for the specific slope. In all, the parameters selected and the structure of the classification system were tailored to the rock, site and engineering situation encountered.

iii) Each rock slope was assessed by the parameter constellations in Cause and Effect space. The intensity and dominance of the parameters allowed an initial evaluation of the critical parameters at each slope. This two dimensional

presentation of parameters, in terms of the effect on the system and the system effects on the parameters, allowed an initial appraisal of the principal mechanisms occurring at the slope and the role of the parameters involved.

iv) The ranking of the slopes was established by the average system intensity from the Cause and Effect plots which is a function of all the interactions intensities and not solely the sum of the independent parameters, as in traditional classification systems. A preliminary sensitivity analysis of the classification system showed that the rating system had the most influence on the average intensity of each slope system and the Cause and Effect plots.

v) An alternative classification system was proposed that takes into account the synergy between the parameters, i.e. their combined influence to either benefit or impair the stability of the slope.

8) The author introduced existing systems concepts to the methodology as a means of providing further understanding to the nature of rock engineering parameters, interactions and pathways. Although much work needs to be done on this subject, it does show further insight into the development of models of different complexity. The concepts pertaining to control systems were shown to have direct ramifications for rock engineering, in terms of excavation technique and stabilization methods as presented by the rows, and columns of the interaction matrix, thus providing the fundamental nature of these activities.

9) The scheme for implementing the total methodology within the phases of the rock engineering process was presented through cycles of information, information interpretation and engineering implementation. The interaction matrix provides the structure for storing information, directing its interpretation and the consequences of implementing the engineering. The whole approach is directed by the engineering objectives. Initially the methodology is applied by an analytic modelling perspective, by breaking down the problem from the engineering objectives to the required parameter resolution. When the base level of parameter resolution is established, the model is built up using the synthetic modelling approach as it then

contains the necessary rock, site and engineering factors for the circumstances that are faced. This provides the basis for the optimum engineering implementation of control.

9.3 Recommendations for Further Work

The development of a rock engineering systems methodology has demonstrated the need for an all encompassing approach and framework in which rock engineering is performed. The main basis of the methodology is the continuing development of the geomechanical model throughout the engineering process. This is pursued by a systems interpretation of the relevant rock, site and engineering parameters for the engineering situation. The interaction matrix has provided the central presentational technique and the focus for the work performed to date. The direction for further work centres on the three parts of the methodology, namely REMIT (Rock Engineering Mechanisms Information Technology), RESP (Rock Engineering Systems Performance) and ONSE (Objective based Network Sequence Evaluation). Consideration also needs to be given to refining the tactical implementation of the methodology by improving classification systems. Limitations associated with the methodology have been presented throughout this thesis. The following suggestions are made to highlight where further work is required and where the research can be directed in the future.

1) REMIT: Rock Engineering Mechanisms Information Technology.

i) Parameter Hierarchy

The REMIT phase of the methodology, which has been the primarily concerned of this thesis, is the fundamental knowledge base and structure of rock engineering parameters, interactions and connections. Inherent within this part of the methodology is the hierarchy of parameters and the resolution of parameters. This aspect has so far been pursued subjectively and by intuition. It is necessary to develop our understanding further into how to break down the parameters from the initial sub-divisions of rock, site and engineering, so that each hierarchical level has some fundamental meaning. In

systems theory, parameter hierarchies are based on emergent properties such that the interactions between parameters on a lower level form a new parameter on a higher hierarchical level. Presented in Chapter 4 was a comprehensive list of rock parameters categorized into a hierarchical structure. This suggestive hierarchy attempted to break the parameters down according to a reduction in the scale of the parts of the rock mass. Structuring the mechanical attributes in a hierarchy however becomes conceptually more difficult. One of the major reasons for this is that many of the rock properties used in rock engineering analysis are not fundamental properties but functions of the testing method and/or are empirically based. Analysis using parameters with energy units was suggested as a possible solution to this problem, as this would involve integration of conditions throughout the whole rock mass rather than point properties. But for the purposes of practical implementation this would require the measurement of a new suite of parameters.

Given the inherent difficulties in developing a truly physical parameter hierarchy, attention may best be placed on adjusting the hierarchy to suit our requirements. The parameter hierarchy is intended to simplify the parameters so that analyses can be performed at different levels of complexity. In Chapter 3 it was suggested that classification methods and numerical analysis use parameters at different levels in the hierarchy. Accordingly, engineering geological parameters are considered to be located at coarser parameter resolutions than those used in numerical analysis (and detailed pathway systems analysis). It has been commented that the parameters used in classification systems should be related to those used in more detailed analysis, both being representative of the geomechanical phenomena to be defended against. To this end, there is a need for these to approaches to be linked.

ii) Engineering Geological Classification Systems

One of the current applications of the methodology is the engineering classification of rock masses by virtue of the interactions between the parameters. An initial tactical application of the methodology was presented in Chapter 7 and the limitations discussed at the end of that chapter. The pursuit of an improved classification methodology is considered a necessity in rock engineering. There is a need for a technique that combines multiple rock engineering and rock mass attributes into a rapid and relatively

simple technique. The author believes that many rock engineers perform such a process by intuition, rock mechanics knowledge and knowledge of precedence, without the aid of a formalised approach. The difficulty is making a science out of the art. The author has discussed throughout this thesis, the deficiencies in existing rock mass classification systems and finds it very difficult to justify how and why they work. The suggested use of rock mass classification rating values in numerical analysis, due to the difficulties in obtaining rock mass parameters at the scale of the rock engineering situation, further justifies the need for a more coherent approach to rock mass classification. Furthermore, given the inherent complexity of rock masses and the difficulties that will always be present in adequately modelling rock mass behaviours, the need for a short cut method is clearly necessary.

The direction advocated in this thesis is to consider the interactions and coupled nature of parameters and the A-7 Autopiste rock slope case study showed an approach for improving the classification methodology. Several aspects of this approach, however, need further research.

A basis for selecting parameters is required so that the classification technique can be objectively applied to any situation. Major difficulties encountered in using the interaction matrix are the treatment of rock mass anisotropy, inhomogeneity and spacial variations. Currently, the leading diagonal terms of the matrix have referred to global rock mass properties, e.g. discontinuity orientation, discontinuity aperture and roughness. For each discontinuity with a specific orientation, the aperture and roughness may vary throughout the trace of the fracture. Some parameters are highly dependent upon multiple discontinuity attributes such as water flow, which is controlled by the fracture connection network. The interactions related to the engineering geological parameters require further definition for coding techniques to be applied objectively.

The nature and meaning of the coding also requires further analysis. The dilemma encountered in coding the interactions for the A-7 Autopiste rock slopes in Chapter 7 was that despite the consequence of some interactions being much greater than others, the coding value assigned to some interactions was the same, as they had the same interaction intensity. Therefore, it appears that the parameters selected should be of

similar magnitude and scale. The coding and parameter ratings techniques need to be studied so that the final classification system output is not biased. One factor influencing this is the summation of the interaction intensities in the rows and columns of each parameter, as well as the numerics of the coding and rating values.

The presentational technique for presenting the classification output requires further deliberation. It is quite clearly necessary to move away from the use of one numerical value to represent the rock mass behaviour, as in traditional classification schemes. The Cause and Effect plot has several advantages, namely it shows the influence of a parameter on the others and the influence of the system on the parameter in two dimensional space and allows instant identification of the most interactive and dominant parameters. There are however several disadvantages. The interpretation of the whole parameter constellation requires further research. For the A-7 Autopiste slopes, the author found that the interpretation of the rock mass behaviour, in terms of a few parameters at the extremes of intensity and dominance, could only be reasonably managed. An empirical interpretation of the system could be established from more case studies in different rock, site and engineering situations. It would also be advantageous to utilize the wealth of precedent knowledge incorporated within the existing classification systems.

2) RESP: Rock Engineering Systems Performance

This phase of the methodology encompasses the network evaluation of interaction pathways in terms of a process-response system. A major part of this work will be dependent upon the structure of the parameters and interactions established in REMIT. Pathways can only be objectively determined when the interactions between the parameters are further defined. Many of these interactions will be non-linear but can be treated by a piece wise linear relation. Graph theory is a mathematical method that deals with multi-variable system in this way to identify the critical mechanism pathway, and this work is currently being pursued by Yong (1993). This approach alone will not solve the identification of pathway problem. Consideration will also need to be given to role of the rock mass structure in defining geometrical attributes and instability scenarios

3) ONSE: Objective based Network Sequence Evaluation

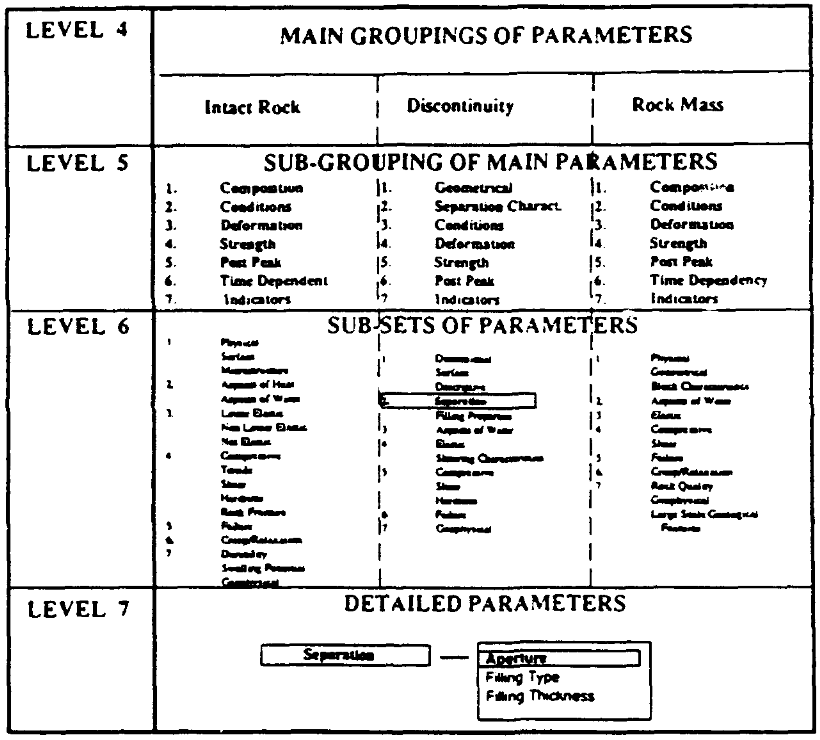
Incorporating the objectives into the systems approach is essentially the interfacing of soft system with hard system methodologies. This poses one of the most challenging aspects, as the objectives are not only difficult to define but also difficult to integrate objectively into the hard systems approach. Another challenging situation is the implementation of the methodology from the objectives to identify the mechanism pathways of detriment to the engineering and site circumstances. Given that all the parameters and interactions may not be known, it is necessary to consider how much information is required before a mechanism pathway analysis can be performed, especially as the aim of the methodology is to rationalize and optimize the rock engineering process.

APPENDIX 3

Definition of Rock Parameters

(sources from Appendix 4-1)

<u>KEY</u> LEVEL 4 All bold words in capitals & underlined.
LEVEL 5 All bold words in capitals.
LEVEL 6 Bold words with initial letter in capitals.
LEVEL 7 Bold words with no capitals, (except for specific names & abbreviations)



Parameter levels as structured in Figure 4.6

abrasivity The resistance of a rock sample to attrition and impact forces; tests in use include Los Angeles and sand blast.
absorption The ability to incorporate fluid (water) into the molecular structure of the rock.
acoustic wave velocity The velocity of high frequency sound waves in testing and strain measurement.
adhesion The bonding and resistance formed by the rock surface.
adsorption The ability to incorporate fluid on to the surface of the rock.
aperture The degree of separation between one joint wall and another.
apparent cohesion Shear resistance at zero normal stress.
Aspects of Heat Thermal properties of intact rock.
Aspects of Water Intrinsic rock properties but only relevant with the presence of a fluid or a gas.
asperity inclination angle The inclination of the individual surface roughness components.
Atterberg limits The physical properties of fine grained soils as related to their moisture contents.
biaxial Stress state where the minor principal stress is zero.
Beam test indirect tensile test where a beam of rock is loaded at its centre to initiate tensile failure.

Block Characteristics The attributes of blocks of intact rock defined by the discontinuities.
block shape The shape of specific blocks being classified, usually described as blocky, tabular or columnar.
block size The average diameter of a typical rock block in the unit to be classified.
body wave velocity The velocity of elastic waves that travel through the body of the transmitting medium and thus are unaffected by the presence of the boundaries.
Brazilian test. An indirect tensile strength test where a rock disc is placed between platens in a compression test machine and loaded to failure across a diameter.
brittle - ductile transition stress The confining pressure at which the post peak reduction in strength disappears and the behaviour becomes fully ductile.
brittleness index 1) The ratio of the fall of in peak strength to residual strength divided by the peak strength 2) The ratio of compressive strength to tensile strength.
bulk density The density of a given volume of rock mass including intact rock, discontinuity, infilling, voids and water.
bulk modulus Ratio of hydrostatic stress to the volumetric stress that it produces.
capillarity The ability of a fluid to move through small voids or cracks due to the surface tension of the fluid.
cementation degree The amount of cement between the grains compared with the total material.
clay fraction The percentage of clay minerals compared with the total specimen; indicates, in part, the swelling potential.
coefficient of thermal expansion The one dimensional strain caused by a given change in temperature
colour index Percentage of dark minerals in a rock, relates to ferromagnesian minerals.
COMPOSITION Fundamental, physical & index properties excluding products of its mechanical behaviour.
compressibility modulus The ratio between an isotropic stress change and the corresponding volume change per unit length.
Compressive The strength of a rock caused by the application of normal stress in a single direction.
CONDITIONS Properties of imposed states or boundary conditions for the rock.
conductivity The ability to allow the passage of electrical current through a rock material.
crack location Descriptive of the position of flaws within the microstructure either being through grains, grain boundaries, cement, matrix etc
crack porosity The porosity of cracks located within the microstructure of the rock material.
crack shape The geometric configuration of flaws.
Creep/Relaxation The time dependant deformation of rock under stress- characterized by three phases, primary - rate of strain decrease due to "elastic" flow, secondary - constant rate of strain, permanent deformation, Tertiary creep increase in strain rate until failure.
DEFORMATION Change in size or shape due to applied stress.
deformation modulus The ratio between a given normal stress change to the linear strain change in the same direction (all other stresses being constant)
density Mass per unit volume of rock.
Descriptive Terms used to describe components & features of joints which may have some bearing on their mechanical behaviour.
dielectric constants The constant of a rock material representing the insulator or non conductor of electricity.
Dilation angle Ratio of plastic volume change to plastic shear strain
Dimensional Attributes of discontinuities represented by their orientation, location or length.
direct The load at failure determined from a pull test, i.e. by divergence
DISCONTINUITY PARAMETERS Properties of a single discontinuity.
ductile A rock is ductile when it can sustain further permanent deformation without losing its load carrying capacity.
Durability An indication of ability to resist wear and degradation from erosive agents.
Elastic Property of material which returns to its original form or condition after the applied force is removed.
ENGINEERING PROJECT These relate to the engineering aspects of the project and include the dimension of the project, excavation method, rock stabilization and financial aspects; these all influence the economy and stability of the project.
faults Discontinuities where appreciable displacement has occurred

field displacement tests Direct measurement of displacements of in situ rock masses in the project environment.

Filling Properties The properties of material within a discontinuity.

filling thickness The thickness of the filling material only; usually, but not always, the same as aperture.

filling type Types include brecciated rock, clay, sand or mineralised material such as slickenslided growths or pressure solution calcite.

fissility degree Qualitative assessment of the amount of laminations within a sample of intact rock.

folds A flexure in rocks; that is a change in the amount of dip of a bed.

fracture toughness A parameter expressing the materials resistance to crack propagation or the fracture energy consumption rate required to create new surfaces.

generic type Used to describe the type of joint or joint set, be it a bedding plane, tension, shear, cleavage, fault etc.

Geometrical Parameters Based on the geometrical attributes of discontinuities.

GEOMETRICAL CHARACTERISTICS The character of a discontinuity based on its geometrical attributes.

Geophysical The use of indirect methods, seismic, resistivity, magnetic or electrical etc, to determine the properties of the rock material or mass.

grain density The density of solid material(grains) only.

grain fabric Describes the arrangement or pattern produced by the orientation and shapes of the grains.

grain orientation The preferred direction of one of many grains in the rock fabric.

grain shape The geometric shape of individual grains.

grain size Refers to the specific dimension of individual grains.

grain size distribution Used to show the variation in the dimension of all the grains within the rock.

grain texture Refers to the physical appearance of the grains including the geometric aspects of and the mutual relation among the grains.

hardness Essentially a surface strength property directly related to the test method.

hydraulic conductivity A medium has unit hydraulic conductivity if it will transmit in unit time a unit volume of ground water at prevailing kinematic viscosity through a cross section of unit area under a unit hydraulic gradient.

indenter hardness The force required to cause indentation by a cone, divided by a constant that measures the cones shape and area.

INDICATORS Properties, parameters or features which are influenced and suggest the state or behaviour of the intact rock, discontinuity or rock mass.

indirect The tensile strength determined from the Brazilian test, bending test or other means where direct tension is not applied.

INTACT ROCK PARAMETERS Rock containing no discontinuities.

internal friction angle The tangent of the linear strength relation between shear stress - normal stress for an intact rock.

joint cohesion The intrinsic strength of a joint at zero normal stress.

joint dilatancy A joint behavioral term describing the separation of a joint at constant normal stress where dilatancy is permitted.

joint displacement A joint is defined as having minimal displacement although frequently some displacement occurs influencing the shearing behaviour of the joint plane.

joint formation Description relating to the circumstances of how the joint originated.

joint frequency The number of joints per meter in a particular joint set.

joint friction angle The angle between the axis of the normal stress and the tangent to the Mohr envelope at a point representing a given failure- stress condition.

joint intensity Synonymous with joint frequency.

joint normal stiffness Determined from the slope of the normal stress normal displacement curve of a shearing discontinuity; normal stiffness is non-linear, but is frequently assumed to be linear.

joint shear stiffness Calculated as the slope of the shear stress - shear displacement curve.

joint spacing The mean of the distance separating joints in a particular joint set.

joint termination Joint sets can be persistence but the degree of persistence often depends on the stress history resulting in joints terminating at the intersection of other joint sets.

joint wall compressive strength Defined by Barton & Choubey(1977); unaltered walls have similar strength to that of intact rock.

joint roughness coefficient A quantitative rating of the roughness degree as determined by Barton.

Large Scale Geological Features Description of major geological features such as faults and folds.

Linear Elastic A term used to describe a material in which no energy is lost during a loading cycle.
liquid limit The water content at which a specimen passes from the plastic to the liquid state.
liquidity index The moisture content in excess of the plastic limit expressed as a percentage of the P.I.
location The specific location of individual discontinuities in space.
Love waves A surface seismic wave characterized by purely horizontal motion perpendicular to the direction of motion.
m, m' Empirical rock mass strength parameters for Hoek & Brown failure criterion, m' is for non interlocking rock masses or those which have been highly disturbed.
magnetic properties The magnetic properties of intact rock due to its mineralogy.
Microstructure Properties of discrete particles or features forming the intact rock.
mineral composition The mineralogical make up of the infilling material; the naming of individual minerals based on their mineral composition.
modulus of deformation The ratio of stress to corresponding strain during loading of a rock mass including elastic & inelastic behaviour.
Non Linear Elastic A non linear elastic stress-strain response on the application of applied stress but no energy loss on destressing.
normal modulus The modulus of deformation normal to the discontinuity plane.
Not Elastic Or inelastic, refers to deformation where the portion of deformation under stress is not annulled after complete destressing.
number of joint sets A joint set is defined when a number of discontinuities have essentially the same attributes & orientation.
orientation The dip and dip direction or strike of a discontinuity or discontinuity set.
overconsolidation ratio The ratio of the pre consolidation pressure to the present overburden pressure.
p wave velocity The velocity of longitudinal pressure waves or primary first arrival seismic waves.
particle size The size & spread (grading) of the composite parts within the filling.
permeability The capacity of a rock to conduct a liquid or gas; related to the flow velocity & hydraulic gradient.
persistence The length of the discontinuities.
petrographic description A geological description of the grain composition, cement and matrix of intact rock.
Physical essentially fundamental non-mechanical properties of the rock, i.e.dependent on testing method.
plastic A rock is plastic when non-recoverable, permanent deformation occurs.
plastic limit The minimum water content at which a rock sample behaves in a brittle manner.
plasticity index As for intact rock, used to assess swelling potential; the numerical difference between liquid limit and plastic limit; represents the range of moisture content at which a material is plastic; related to the swelling potential.
point load strength index The strength of rock determined from the point load test apparatus.
Poisson's ratio Ratio of radial to axial strain in an elastic medium.
polyaxial Special triaxial test. The strength when three independent variable stresses are applied to opposing faces of a cube of rock.
pore pressure The induced pressure in the pores of a material generated by a change in loading.
porosity Ratio of the volume of voids to the total volume of the intact rock.
POST PEAK Properties indicative of rock behaviour beyond the peak strength.
primary permeability The ability of intact rock to conduct or discharge fluid(water) under hydraulic gradient.
radioactivity Rock containing minerals in which there is a spontaneous disintegration of unstable atomic nuclei which is accompanied by emissions of alpha and beta particles and/or gamma rays.
Rayleigh wave velocity A seismic wave propagated along a free surface in which the particles have a retrograde elliptical action.
rebound number Relates to strength & hardness by use of a Schmidt hammer where the rebound from an applied force is measured.
residual cohesion The cohesive strength after appreciable displacement.
residual friction angle The post peak strength reduction in the friction angle.
resistivity The electrical resistance of current across a rock material.
rigidity modulus Synonymous with shear modulus.
Rock Fracture Refers to the initiation of fracture on a micro scale.
rock mass classification rating A numerical value representative of a summation or product of rating values given to selected parameters of a rock mass.

ROCK MASS PARAMETERS Properties of the rock mass considered as a whole combining intact rock & discontinuity parameters together.

rock noise The audible response of a rock to applied stress or destressing.

Rock Quality Principally a qualitative assessment of the state of the rock mass.

roughness The degree of irregularity on a joint surface.

roughness anisotropy The variation in the degree of roughness at different orientations along the joint surface.

RQD The sum of lengths of rock core pieces longer than 10cm expressed as a percentage of a given total length drilled, usually a core run.

rupture modulus The tensile strength measured by the beam test.

s, s' Empirical rock mass strength parameters for Hoek & Brown failure criterion, it is now though that $s = 1$ or 0, where $s=1$ is for fractured rock, and $s=0$ is for intact rock.

s wave velocity The velocity of transverse shear waves or secondary seismic waves.

saturation degree The ratio expressed as a percentage between the volume of water and the total volume of voids.

scratch hardness The hardness estimated by comparison ..ary reference scale based on the ability of one mineral to scratch another.

secondary permeability The permeability caused principally by the flow of water through the discontinuities rather than the intact rock.

seismic The measurement of the velocity of generated waves which result from the application of an energy source.

seismic velocity The velocity of seismic waves in geological materials.

sensitivity The ratio between the undisturbed and the remoulded shear strength of a soil.

Separation Characteristics The physical and dimensional aspects of the joint aperture and filling.

Separation The attributes of the joint separation.

Shear Shear occurs where a stress is directed parallel to the surface element across which it acts.

shear modulus The ratio between a given shear stress change and the corresponding shear strain change.

shear strength The maximum strength along a failure surface where the stress is directed parallel to the surface element across which it acts.

Shearing Characteristics The behavioural characteristics of joints under shear and normal stresses; joints are assumed to have no tensile strength.

SITE Parameters which depend on the specific location of the engineering project; the influence of these can vary during construction and they tend to be boundary conditions or loading factors.

slake durability index A percentage of the dry mass of a sample after a S.D.T cycle to the dry mass of the sample before the first test cycle. An estimate of the resistance of rock material to cycles of wetting & drying, hence weathering.

solid core recovery The sum of the lengths of pieces of intact rock core of full diameter expressed as a percentage of the total core run.

solubility The ability of a material to dissolve in water.

specific gravity Ratio between the mass of material and mass of an equal volume of water at a temperature of 4 degrees C.

specific heat capacity The amount of energy needed to raise the temperature of a unit of rock by one degree C.

specific storage The volume of water a unit volume of saturated aquifer releases from storage for a unit decline in hydraulic head.

storativity The volume of water that an aquifer releases from or intakes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface.

strain hardening Synonymous with post-peak strength ductile behaviour.

strain softening Synonymous with post-peak strength brittle type behaviour.

STRENGTH The stress state at which a rock specimen ruptures.

STRESS STATE The stress as defined by the components of the tensor characterizing the 3-D stresses at a point.

Surface Properties Directly relevant to the surface state of the intact rock or discontinuity.

surface energy The surface arc per unit area of the crack surfaces is associated with the rupturing of atomic bonds when a crack is formed.

surface roughness Surface expression caused by the mineralogy of the rock; possibly also due to excavation technique; not due to discontinuities.

surface texture The general physical appearance of the joint surface.

Swelling Potential A qualitative grading of the potential that a cohesive, fine grained, sample will expand or shrink with changes in water content; related to clay content, mineralogy and plasticity index.
swelling pressure index The stress required to prevent expansion of a rock specimen when water is introduced.
swelling strain index The maximum expansion of a completely unconfined rock specimen when submerged in water, usually expressed as a percentage.
Tensile Resistance to fracture under tension.
thermal conductivity A measure of the quantity of heat transmitted across a unit cross section in a unit time for a unit temperature gradient.
thermal diffusion The interpenetration of heat into rock by natural movement of their particles.
TIME DEPENDENT Strength properties indicating the behaviour of the rock with time.
total core recovery The sum of the lengths of pieces of rock core expressed as a percentage of the total core run.
trace length The measurable length of the linear trace produced by the intersection of a planar discontinuity with a planar rock face.
transmissivity The rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient.
triaxial Three principal stress states applied to fail the rock; they may be independent but more commonly used for one independent stress state and two equal stress states which are non zero. i.e. not uniaxial.
triaxial creep rate As for uniaxial creep rate except with the application of a confining stress.
ultrasonic wave velocity The velocity of compression and shear waves to give an indication of the soundness of rock or dynamic rock properties.
uniaxial Failure that occurs when two principal stresses are zero.
uniaxial creep rate The strain as a function of time determined from the application of uniaxial stress.
unit weight Ratio of the weight to the volume; also dry unit weight, unit weight (solids) & buoyant unit weight.
viscosity The resistance to a change in the arrangement of the molecules; applicable to weak rocks and rocks under high stresses and temperatures where time dependent behaviour can occur.
void ratio Ratio of the volume of voids to the volume of solids.
volumetric joint frequency The average number of joints per unit area or unit volume of the rock mass.
volumetric RQD The summation of intact blocks bigger than $0.001m^3$, expressed as a percentage of the total rock mass volume.
water content The mass of water contained in a rock specimen, expressed as a percentage of the dry mass.
waviness Large scale surface roughness.
weathering state A description for the state of decomposition of rock due to the influence of the atmosphere and hydrosphere.
yield strength The stress level at which rock ceases to behave elastically.
Young's modulus The ratio between the normal stress in a given direction & the elastic strain in that direction

APPENDIX B

OUTLINE OF DOCTORAL THESIS

"DEVELOPING COMPUTER METHODOLOGIES FOR ROCK ENGINEERING DECISIONS"

BY M K GOKAY.

DEVELOPING COMPUTER METHODOLOGIES FOR ROCK ENGINEERING DECISIONS

A thesis
submitted to the University of London
(Imperial College of Science, Technology and Medicine)

by

Mehmet Kemal Gökay

In fulfillment of the requirements
for the degree of Doctor of Philosophy
and for the Diploma of Imperial College

March 1993

Abstract

The purpose of this study is to produce a decision-support system through a combination of knowledge-base systems and multicriteria decision analyses for excavation design. The main objective is to co-ordinate the necessary guidance for rock engineers in the assessment of multiple project alternatives and hence in the selection of the best approach for development.

The system is equipped with separate compilers for different decision analyses. The main decision procedures of these compilers are operated by consideration of each design parameter individually and the application of a rating system to demonstrate the parameter's importance to overall stability. Once all the parameters have been rated, comparison and/or linking of individual parameters with others to reach a final decision using decision methodologies is rapid.

The decision codification in terms of multicriteria source files or knowledge-bases is prepared in accordance with currently available information from the literature, but the systems are ready to accept knowledge-bases and source files prepared by using experts' experiences. In the case of any decision problem, decision-makers can examine the current conditions presented in four stages of codification in the knowledge-bases and single stage of multicriteria source files to obtain the opinions of the experts throughout the system. If such a file is not in the given system related with the current project conditions, one can be prepared for future application by using one of the sub-sections of the system.

The knowledge presentation techniques were reviewed and the specific rule-based knowledge presentation method was selected to develop a new modified easy-to-use procedure for knowledge-base preparation. The methodologies presented for multicriteria decision analyses are formulated and their procedures are well established and formatted for different applications. A combination of the decision-making concepts and conventional numerical, empirical, and graphical analyses as a user-friendly system has been prepared for more realistic solutions to the rock engineering problems.

Since the engineering includes different sources of uncertainties, due to the nature of the rock masses, uncertainty manipulation procedures have been also included into the system compilers. For the first stage of application, the system is equipped with source files and knowledge-bases considering the rock mass classification, mining methods, discontinuity identification, and stability of the openings and pillars. The system compilers have been developed in a generic manner, and so the knowledge-bases and other decision related source files can be modified, changed, or replaced according to new improvements in the domain problems. The practical use of the design methodologies has been outlined by supplying representative examples.

Outline of Thesis — "Developing Computer Methodologies for Rock Engineering Decisions"

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Notations

AI	: Artificial intelligence.
ASCII	: American Standard Code for Information Interchange.
VAX	: Main frame operation system.
DOS	: Digital operating system.
$q_{(i)}$	: Decision parameters in classified decision representation method.
$e_{(i)}$	: Classified messages in classified decision representation method.
T	: Threshold value.
$x_{(i)}$	: Neuron number in neural network.
$W'_{(i)}$	: Weight of the message in neural network systems.
$F_{(s)}$	: Output signal from the neural cell.
R	: Total rating value calculated for the selected network path.
i, j, l	: Natural numbers.
$d(i,j)$	: Nodal point at network analyses.
n	: Total number of nodes in the selected network.
X_m	: Mean value.
V_x	: Variance.
δ_x	: Uncertainty with inherent randomness.
pA	: Probability of A.
pB	: Probability of B.
$P(H_{(i)}/E)$	: Evidence E shows the hypothesis $H_{(i)}$ is true.
k	: Total number of possible hypothesis.
CF	: Certainty factor sign.
C_x	: Certainty factor of "x".
$CF_{(x/A)}$	: Certainty factor of "x" after related with parameter A.
$CF_{(i)}$	: Certainty factor of decision parameter "i".
$CF(R(i))$	: Certainty factor of neuro-condition "R(i)".
$CF(B(i))$	: Certainty factor of neuro-rule "B(i)".
$CF(B(i))r$	: Resultant certainty factor for neuro-rule "B(i)".
$CF(B(i))t$	: Resultant certainty factor for neuro-rule "B(i)".
$CF(F)t$	: Resultant certainty factor for the final decision "F".

$\mu_a(x)$, $\mu[i]$	: Membership value in fuzzy sets.
M	: Membership space value.
D	: Decision.
μ_D	: Final fuzzy set for decision.
μ_{low}	: Fuzzy set (lower limit).
μ_{high}	: Fuzzy set (Upper limit).
α_i	: Power factor in decision analyses.
$C_{(i)}$	: Decision objectives in decision analyses.
$\cap$	: Combination operator.
$\cup$	: Intersection operator.
U	: Universe of discourse.
$B_{(ij)}$	: Saaty's importance level matrix.
W_i	: Eigenvector.
λ_{max}	: Eigenvalue.
F_a	: Decision function.
L	: Fuzzy expected value set.
$I_{(A)}$	: Incidence value of A.
$I_{(B)}$	: Incidence value of B.
$W_{(I)}$	: Possible incidences in universe of discourse.
PF	: Plane failure.
WF	: Wedge failure.
ANG	: Angle.
P_i	: Decision parameters in the interaction matrix.
$I_{(ij)}$	: Interaction value in the interaction matrix.
RSR	: Rock structure rating value.
Q	: Calculated Q-system rating value.
RMR	: Rock mass rating value.
$MRMR$	: Mining rock mass rating value.
$MRMRc$	: Uniaxial compressive strength rating in the MRMR.
$SRMR$	: Simplified rock mass rating value.
$NATM$	: New Austrian tunnelling method.
SMR	: Slope mass rating value.

RMS	: Rock mass strength.
DRMS	: Design rock mass strength.
RR	: Rib ratio.
RQD	: Rock quality designation.
J_n	: Joint set number in Q-system.
J_a	: Joint alteration number in Q-system.
J_w	: Joint water reduction number in Q-system.
J_r	: Joint roughness number in Q-system.
SRF	: Stress reduction factor.
ESR	: Engineering structure ration in Q-system.
A_w	: Discontinuity weathering modification factor.
A_{do}	: Discontinuity orientation modification factor.
A_{dc}	: Discontinuity condition modification factor.
A_e	: Discontinuity excavation techniques modification factor.
FE	: Finite element method.
BE	: Boundary element method.
DE	: Distinct element method.
σ_1	: Major principal stress.
σ_3	: Minor principal stress.
s, τ_{max}	: Shear strength.
c	: Cohesion.
ϕ	: Internal friction angle.
σ_n	: Normal stress on a plane.
σ_c	: Uniaxial compressive strength.
ξ	: Strain.
υ	: Poisson's ratio.
E_m	: Deformation modulus.
m	: Constant.
s	: Constant.
NRS	: Neuro-rule-systems.
NRS-B	: Basic neuro-rule-system.
NRS-CF	: Neuro-rule-system with certainty factor analyses.

NRS-FD : Neuro-rule-system with fuzzy decision analyses.

FDS : Fuzzy decision systems.

FDS-B : Basic fuzzy decision system.

FDS-M : Multicriteria decision analyses in fuzzy decision system.

HETS : Hierarchical expertise transfer systems.

HETS-C : Hierarchical expertise transfer system by classifier method.

HETS-A : Analytical hierarchical expertise transfer system.

if, and, or,

not, then,

if then,

if and only if,

true, false : Logical operators.

$R(i)s$: Single neuro-condition in a neuro-rule.

V_i , M_i , S_i : Numerical variables in NRS compilers.

T_i : Text display variable in NRS compilers.

FEV : Fuzzy expected value.

FEI : Fuzzy expected interval.

$FV_{(i)}$: Fuzzy variable.

$FE_{(i)}$: Fuzzy expression.

$FA_{(i)}$: Fuzzy adjective.

X_m : Expert defined maximum quantity for a neuro-condition.

$I[i][j]$: Value interval for FEI calculation.

$FEI[i]_{lower}$: Lower limit of FEI.

$FEI[i]_{upper}$: Upper limit of FEI.

RI_i : Range identifier in NRS-FD.

r_i : Range multiplication factor in NRS-FD.

A_{ym} : User defined truth matrix in HETS-C.

Rdb : User defined certainty levels in HETS-C.

$Dg_{(i)}$: Expert defined path matrix in HETS-C.

D_i : Decision alternatives in $D_{g(i)}$.

E_{ab} : Expert defined decision path matrix for "direct" method in HETS-C.

R_m : User defined pairwise ratings in HETS-A.

D_f	: Final decision in HETS-A.
J_i	: Decision objectives in HETS-A.
A_i	: Decision alternatives in HETS-A.
$Rc_{(i,j)}$	: Results from pairwise comparison of the decision alternatives with respect to decision objectives in HETS-A.
$\mu_{FD}(0,1)$	: Resultant decision set in HETS-A.
μ^1_{FD}	: First projection values in FDS.
μ^2_{FD}	: Second projection values in FDS.
h_{FD}	: Global projection value in FDS.
FD_m	: User defined membership values in FDS.
r_{ij}	: Resultant aggregated matrix in FDS-M.
$d_{(ij)}$	: Dominance matrix in FDS-M.

Chapter 1

Introduction

1.1 General Background

Engineering decisions given in rock engineering have been mainly based on the experiences gained from similar cases. The question to be answered in this stage is why the final decision about any action in rock engineering requires deep experience of the problems. The reasons can be explained mainly as a result of unknowns in the rock mass behaviour, and consequently most of the analyses and solutions are based on assumptions which approach the behaviour of the rock mass by modelling. Therefore, design of the excavation of the rock mass requires sophisticated engineering works due to the modelling considerations. Since knowledge of rock engineering is increasing rapidly, design engineers must understand their problems more clearly by using current level of information before reaching any decision. The differentiation of the main design concepts in rock engineering and the research studies which cover them are already illustrated by Hudson (1989), as it is shown in Figure 1.1. As described in many text books, examining the field of interest from the higher levels gives advantages of the broader view about the problems and in addition helps the understanding of the

interconnected sub-disciplines about the problems. Responsibility of the design engineers covers definition of the design parameters, their interactions and their analyses. These can only be satisfied by analyzing the entire concept, using the physical sciences and other available sources which can be scientific theories, and analytical and empirical techniques in the case of rock engineering. Since the required design procedure is unique for each design problem, a wide range of human experiences is necessary to solve it for different conditions.

A starting point for systematic study can be the previously reported experiences of the researchers to see if there is available recommendation based on good practice. The scale of the quarries opened for the construction of Pyramids in Egypt 5000-6000 years ago demonstrates the knowledge of the early engineers in quarry works. Similarly, the tunnel excavated in the Sinai Peninsula approximately 5000 years ago (Bieniawski, 1984) shows the ability of mankind who mined minerals and opened a passageway in

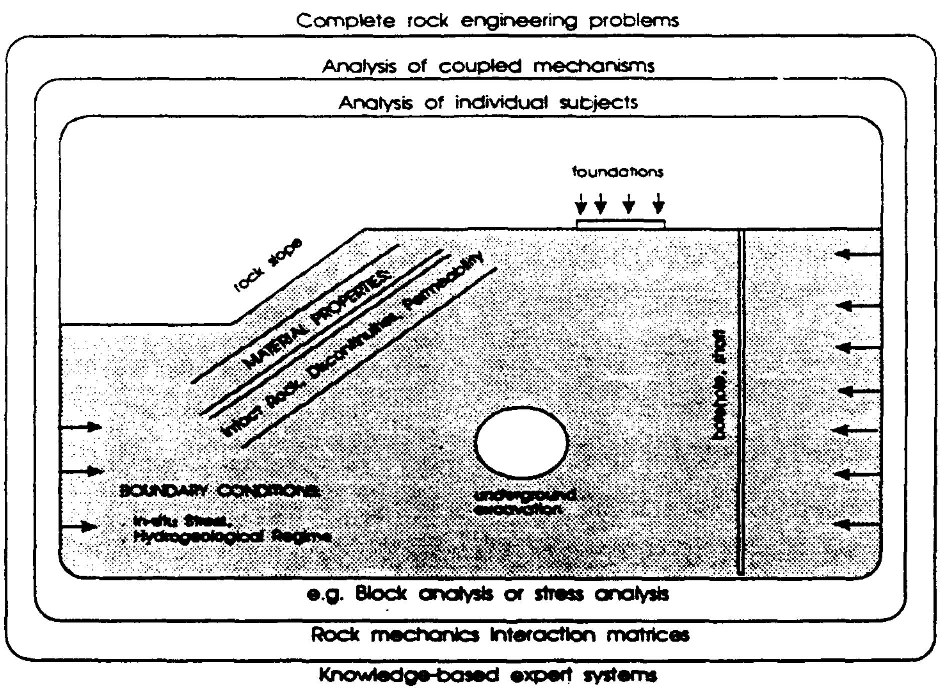

Figure 1.1 Interrelation of the rock engineering design subjects (from Hudson, 1989).

everyday life requirements. However, most of this knowledge and experience was not transferred to new generations and has been lost gradually. In modern times, since the applications related with rock engineering began to be documented, the amount of knowledge and experience which has been transferred has increased.

Bieniawski (1984) reviewed most of the documented tunnel works, and stated that usage of empirical design methodologies based on experience was started long before science and engineering could supply the logic and theoretical background knowledge. In the last 25 years, researchers all over the world have been developing the principles of rock mechanics, including methods and techniques of rock testing, the definition of rock failure mechanisms, and many others. Similarly, the main fundamental rules of the excavation stability analyses have been defined in terms of several modelling approaches for different rock mass conditions. Since then, these modelling techniques have been improved to represent behaviour of rock masses more realistically.

In addition to these improvements, progress in computer technology and programming languages has made it possible to prepare programs which require large data storage capacity and fast calculation steps. Further progress in programming languages has been expanded by the introduction of logical programming techniques for non quantitative problems. The knowledge transfer method used in all human history which is based on the transfer of the good practice from the master expert to the newcomers has begun to be accompanied by the procedure which covers the knowledge and experience transfer from the master experts to the logic program steps. The subjects covered by this new area have been applied to the engineering practice in different application methods and one of them has been named as knowledge-based expert systems. The main purpose of such a system is collecting the information and experiences accumulated in the field of interest and codifying them into a series of knowledge-bases which can be interrogated at any time in future for similar decision circumstances. This prevent the lost of knowledge and experience which occurs because of different reasons many times in human history.

Peck (1981) reviewed the failure of certain rock engineering constructions and concluded that the failures occurred mainly due to oversight of the problems not because of quantitative inaccuracies. He also pointed out that some of those failures could have been avoided by using knowledge available at that time. Therefore, he suggested the implementation of analyses or procedures should include non-quantitative and non-numerical methods for the final decision. These and many other examples demonstrate the importance of the expert's knowledge transfer procedures and their availability for every design applications. At the beginning of computerisation in earth sciences, storing the numerical data, reports, maps, and related calculation steps as programming steps was believed to be enough for directing and guiding the design procedures. However, it has since been realised that they cannot be used to keep the experts' decision procedures and experiences because of the limitations in available programming languages.

Sagan (1980) gave a speculative estimate of the human brain storage capacity as about 10^{14} bits of information, which is equal to the capacity of about 150 million personal computers. The differences between the capacity of the human brain and the level of computer capacity should not be interpreted directly to conclude no program running in the computers can perform at the same level as experts. Research in psychology proves that, it can be possible (Slovic and Lichtenstein, 1971) to some extent. The apparent contradiction between the great capacity of the human brain to store information and the good performance of relatively simple computer decision models can be explained by the limitations of human capacity in decision making. Results led researchers to conclude that it is possible to replace man in certain situations by his decision strategies (Figure 1.2). This statement might seem impractical, but the expertise and knowledge of the domain expert can be built-in as a transfer mechanism within a system (Winston, 1992) for choosing the proper solution for a given problem. The selection of the solution is based on the purpose of the project, decision parameters, and interactions between them. These and other ideas in artificial intelligence concepts have then become the main background of logical programming techniques. After introducing the information technology and developments in the knowledge representation techniques, it was understood that some of the conceptual knowledge and practical human experiences

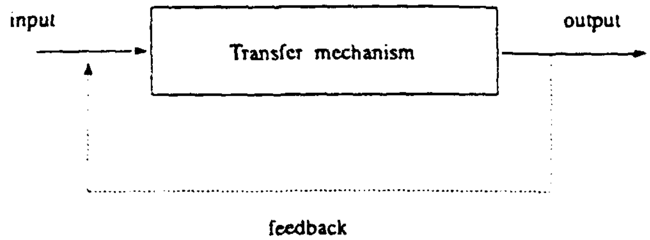

Figure 1.2 Description of the decision steps in terms of transfer mechanisms.

can be stored in the computer as logical propositions. One of the first application of the expert systems in earth science was PROSPECTOR (Duda *et al.*, 1979a). It is a computerised geological consultant system that is intended to aid trained geologists in evaluating project sites for particular ore deposit types. Similar specialized computer programs in mining and geotechnical science have been prepared for instructing and guiding the professional decisions. These logic programs are knowledge intensive and they are ready to evaluate the decisions according to their defined input files, which are called knowledge-bases.

1.2 Purposes of the Research

This research study aims firstly to prepare a user-friendly knowledge-base expert system which can be used for the design of excavations by the application of rock mechanics principles. The second purpose is to analyze the hierarchical decision methodologies for programming as practical computer methods for multi-alternative decision cases. The decision procedures will be examined to guide the rock engineers in many different decision circumstances. As an example, numerical and empirical modelling techniques, their procedures and the meaning of their results must be described to inexperienced engineers. Therefore, the proposed system should be seen as a means which enables the non-experts to use and interpret the numerical, analytical and empirical models more efficiently with the help of expert defined procedures for specific or general cases. The problem is the presentation of the experts' knowledge and experiences in a practical decision-support procedure. Because the design problems and their solutions in rock

engineering mostly depend on interpretation of the input data and results of the analyses, the advice and recommendations of the domain experts are extremely important.

One of the most significant characteristics of engineering design is the dynamic procedure of its structure. It can be described as a set of activities that take place in time. At any stage of this process, if the questions related with project are adequately answered, the answers will lead to better design than if the questions had not been adequately answered. Therefore, the information systems, or expert systems, should provide sufficient details of the qualitative and quantitative information and procedures about the expected problem conditions. It should be borne in mind that the proposed decision models are not prepared to replace the design engineers or provide complete precise answers to the problem defined. Instead, they produce information that validly guides the thinking of the design engineer concerning the decision conditions.

Since the description of the information and related procedures is different for each problem case, sometimes different experts have different answers for the same problem. At this stage, the engineer should examine all the possible explanations and design procedures. Therefore the decision system offered in this study provides knowledge-base compilers which can accept different experiences and information from different sources as a predefined sets of knowledge-bases or data files. This actually might initiate a new range of application in the rock engineering applications.

To this end, preparation of a knowledge-based expert system was selected as a first aim in the study. The requirements of the expert systems which should include the expert knowledge and experiences in rock engineering lead to new developments of the knowledge-base structure and a new expert system compilation program during this study. In order to manipulate the uncertainty of the experts and the user and represent the information which can be used simultaneously during the decision evaluation, the rule-based knowledge representation method was modified totally and a new understanding developed in knowledge codification in knowledge-base structure. In addition, this structure is used to describe uncertainties by means of certainty values and fuzzy concepts. Three different expert system shells have been prepared to handle any

knowledge-bases prepared for different decision applications according to the developed knowledge-base format structure. Other than these decision procedures, decision concepts defined in other disciplines are explored and some of them are programmed to obtain computerised decision procedures.

Another aim is the preparation of a computer system which can govern the decision methodologies and related decision-support programs to combine the several application conditions as a whole. In this way, it is expected to reach a stage where the rock engineering problem can be analyzed by means of all possible methods with the help of all related expertise and information. To do this, the proposed program's main structure was formed and it has been equipped with decision and decision-support programs. The programs included in the system are the rock mass property database structure, rock mass classification procedures, discontinuity analyses, decision parameter interaction procedure, numerical analyses procedure, and many other possible steps are illustrated for further research applications. The intended aim has been reached by presenting the applicability of logic programming in rock engineering subjects. All the developed programs and other studies described are believed to create a new understanding in rock engineering and to open new dimensions to the research when they are interpreted within the rock engineering system philosophy.

1.3 Content of the Thesis

The flow chart of this dissertation is presented in Figure 1.3. As it is seen, the thesis consists of eight chapters and it can be divided into five main parts according to the contents of these chapters. Thus, while the first two parts review the basic background of the field of study, the other parts describe what has been achieved in order to reach the defined purposes and present the results of the study. Part I is the description of the research problem as an introduction. The reasons for the research work are given and the main purposes are outlined. Part II presents a brief background of knowledge transference and the main considerations of the excavation design. It consists of three chapters and each covers the related information about the selected title. Chapter 2 constitutes the information about knowledge-base systems and knowledge presentation

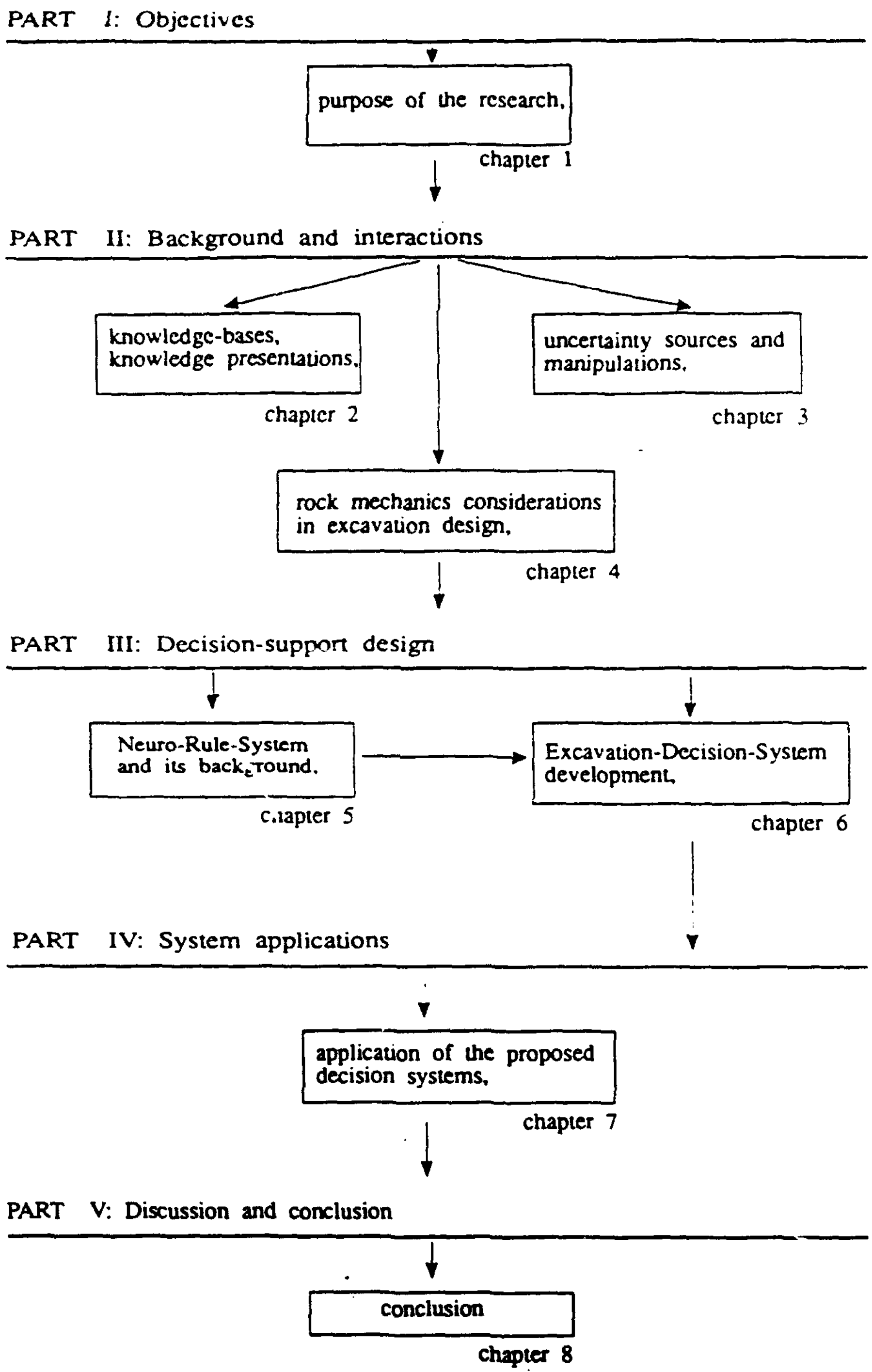

Figure 1.3 Flow chart of the research in this dissertation.

of knowledge-bases is discussed. Disadvantages of the conventional data files are mentioned to demonstrate the advantages of the logic programming techniques. Chapter 3 shows the difficulties of the decision making with uncertain sources of information. The methods for dealing with decisions under different conditions are described according to different available methods in this field. Chapter 4 demonstrates the main design considerations of the excavations in/on the rock mass. Methods of the rock mass description, the excavation stability considerations and design parameters are described to present the level of knowledge in rock engineering related with the excavation design procedures.

Part III includes the main developments and the results of the last three year's. The description of the new knowledge representation method is explained with its differentiation from the case of classical logic, certainty factor, and fuzzy decision procedures. The knowledge-base structure for these three different decision analyses are described with their formatted structure. The methodologies used in their compiler preparation are given to illustrate their working principles as a guidelines. In Chapter 6, the features of the decision-support systems are explained with the presentation of developed conventional decision support procedures.

Part IV consists of the applications of the developed systems. It includes sections to demonstrate the usage of their decision methodologies. The systems applicabilities are presented by preparing the related data files and series of knowledge-bases according to selected decision examples.

Part V is the conclusion and summarises the research. It includes the author's discussions about the problems encountered during the study and illustrates the future direction of knowledge-base decision support systems in mining and rock engineering.

Chapter 8

Conclusions

8.1 Summary and Discussion

The design engineer in the rock engineering field has difficulties because there are no suggested general design procedures. Many decisions during construction of the excavation should be taken according to experience. In this study, the related subjects have been examined to see if it is possible to determine a methodology for a standard excavation design procedure. Because of the uncertainties in the nature of the data obtained from the rock mass, it is already known that the results from any analyses are only approximations. Therefore, here are offered different decision methods for the case of rock mass classification, rock type determination, failure stage of the rock mass, rock load height over the tunnels, free block identification at the roof of excavation, and others. These decision analyses relating to rock mechanics have been described in Chapter 4 with a review of their steps and their decision parameters. Chapter 4 includes the description of the rock mass classification and rock material identification procedures. Description of the rock mass was one of the early methods in attempting to define an empirical design procedure. The rock mass classifications were presented

with their suggestions of possible excavation and support type according to the defined rock mass classes. These methods are also examined in Chapter 4 to determine what the authors (experts) of these methods used to describe the rock masses. The appearances of the new rock mass description parameters illustrate the improvements in the rock testing methods and the knowledge of the rock engineers.

It is also found that the rock mass behaviour is dependent on the its structural features. The conditions of the failure cases were also reviewed in this chapter. Therefore, the description of wedge, plane and toppling failures given are illustrated by their plots on stereonets, which increases the speed of engineering decisions for the given discontinuity data. If there are no discontinuities in the rock mass or they are random and very separately distributed, the rock mass can be analyzed with elastic closed-form solutions to examine stability conditions. Similar methods are also used in numerical modelling and the rock mass is modelled with the necessary assumptions. When the induced stress conditions are defined, the failure conditions of the rock mass are checked according to available, suitable failure criteria.

After obtaining the information about these basic decision parameters, the design engineers should consider the given conditions. However, the decision is not easy in many cases, and sometimes the decision process should be guided by means of a more knowledgeable person (expert). Chapter 2 earlier explained the procedures developed in order to help or guide the decision-makers in their decision evaluation. This guidance can be computerised by means of logic programming techniques. The resultant expert systems programs are now available for different purposes. Chapter 2 explains the main differences between the expert systems and their knowledge representation methods. Preparation steps of the expert system are described and the reasoning of the expert systems is demonstrated in this chapter.

During the decision evaluations, a second point which should be considered is the certainty of the described decisions (as a knowledge engineers) in the knowledge-bases and the certainty of the users while answering the knowledge-base questionnaire. All the conventional programs are programmed to check a limiting values to see if the

decision condition is ***true*** or ***false***. However, if the decision is based on classical logic procedure, there is no chance to include the degree of belief about the selected decision. In order to express the degree of certainty for the given decision, uncertainty manipulation techniques have been introduced by different researchers. Chapter 3 therefore reviews these researches and their main procedures are presented with examples.

Certainty factor theory classification methods, possibility theory and classic logic methods are some of these methods. The introduction of the interaction matrix in fact is aimed to relate parameter interactions for any excavation design, but in this study it is used to define critical decision parameters before the knowledge-base preparation works or during the evaluation of the expert systems. There are 3 knowledge-base methodologies developed during this research by using the classical logic, certainty factor, and fuzzy set concepts. If the decision-maker wants to reach a decision by using yes/no questions, the NRS compiler can be used; if the certainty about the selected decision needs to be entered, the NRS-CF compiler can be selected; and the NRS-FD compiler has been developed for the fuzzy decision applications. Chapter 5 describes the knowledge-base systems and their logic for decision. Chapter 6 is included to demonstrate the prepared decision support programs and their applicability as a branch of Exc-Dec program. The selected subjects for decision support programming are the conditions which the experts in rock mechanics condition to be the main conditions for excavation design. Therefore, rock mass classification, rock mass properties database, discontinuity analyses for stability, and the induced stress effects on the designed excavation are all defined and their programs are explained with examples. Chapter 7 includes applications of the Exc-Dec program which is still under development. Necessary information was obtained from the literature and codified for the two application sites which were Parys Mountain underground mine and Mountsorrel quarry. The knowledge-bases about these sites are presented later in the Appendices.

Since the aim was the review of decision procedures in general decision evaluation and their application with the rock engineering cases, the examples and the decision support systems which deal the different subjects are arranged in such a way that they are all

representative of the programs in those subjects. The author's expectation is the extension of this research and preparation of full scale expert-guided design procedures for different purposes.

8.2 Main Conclusion

Resent years have been the most productive for the computer industry. The development of personal computer technology means that every field and office engineer potentially has a personal computer. If these engineers are supported not only by the conventional analysis programs but also by logical advice for their designing difficulties, they can be guided during their designing action with the services of the experts, through expert systems.

The logic procedures which have been developed for 10 or 20 years are all aimed to present human logical reasoning in the computer's operation systems. There are many methods developed for the representation of logic knowledge in computers. One of the main knowledge capturing methods for computer programs is the rule-based knowledge representation method and it is applied in expert systems as a production rule language. Applications of this method in rock engineering subjects have been given by several researchers. However, it is realised that knowledge description by this method requires some repetition in certain cases. Besides this, it is not practical to change a rule as quickly as it is reported. In order to overcome these points, neuro-rule-system procedures have been developed and presented during this study. The knowledge representation method with this system is explained in detail in Chapter 5 and its applications are presented in the Appendices. The prepared NRS systems are not totally completed but, the research objective was simply their development. Their application for the example cases shows the practicality of the systems.

From the achievements that have been reached during this dissertation, as listed as in the following section, it can be understood that the design procedure for any excavation in a rock mass becomes clearer if the following information can be obtained before the actual design procedure starts. This information is:

1. Rock mass type description,
2. Rock mass classification,
3. Rock structure definition,
4. Definition of the critical decision parameters,
5. Numerical calculations for the required conditions,
6. Quick decision evaluation for the selection of alternatives,
7. Decision evaluation by combining the different opinions,
8. Decision evaluation with the assistance of the experts,

The decision about any rock engineering alternative and objectives can be considered for analyses according to the available decision procedures. In fact, when the number of decision alternatives and decision objectives is large, this may be the only way to evaluate the best alternative as a decision, because there are many points which cannot be considered and evaluated as an instant decision. In this respect the requirement of the decision methodologies in rock engineering becomes obvious, in particular when there is a definite uncertainty in the given decisions. The design engineers should consider the reliability of the final decision according to their belief in the selected sub-decisions about each individual decision parameters. These points are considered and the decision in rock engineering analyzed by the available methodologies (presented in other branches of sciences). The decision methods are computerised and their applicability improved. Therefore, the computer methods developed for rock engineering in fact include the new interpretation of the available decision concepts in artificial intelligence.

Original specific contributions made by the author:

The research which has taken place during this study covers the following points and contributions to the knowledge of engineering research in rock mechanics.

. **The literature about rock mass classification has reviewed and 110 papers reporting rock material and rock classification schemes were checked for their classification methodology and classification parameters. The descriptive outputs from the rock**

mass classifications are reported and their improvements in the time is documented.

. Rock engineering research results in excavation stability analyses are listed and their basic characteristics are interpreted for the aim of excavation design.

. Uncertainty manipulation techniques are reviewed to find a reasonable application procedure. Consequently, multi-objective decision procedure, certainty factor and fuzzy decision procedures described in the literature as a basic theory are applied to the rock and mining engineering subjects with practical decision procedures.

. Expert system methodologies are reviewed and production-rule language tested for presenting rock engineering problems. However, the problems related with these languages led the author to produce an alternative knowledge representation method after investigating the other representation methods. The developed knowledge representation method which can be also called a modified rule-base system, is organised into a working expert system shell using C programming languages. The created system was then named by the author as a Neuro-Rule-System, NRS, due to its similarities with the basis of neural-networks and rule-based systems.

. The author produced a NRS compiler as a expert system shell, which uses the developed neuro-rule knowledge representation to facilitate the classical logic decision procedures.

. After obtaining considerable experience with the NRS compiler, the NRS-CF compiler was developed as a separate expert system shell. It has similar compilation principles as the NRS, but the decision is directed by the certainty of the users and experts in this case. This procedure helps capture the uncertainties of the users and experts for the defined final decision.

. As the last step of the NRS compiler series, the author has been working on a NRS-FD compiler, which is going to be an expert system shell with the capability of fuzzy decision manipulation. The system's reasoning and main governing compilation

facilities have been prepared, but its decision procedure steps required further development according to its procedure.

. The author has presented a decision support device for the field engineer (which is the one of the main points of this study) and developed a user interface environment to activate the developed programs and necessary computer usage facilities to obtain required information.

. The author has provided to give a fuzzy decision procedure for decision alternative selection cases. Consequently, FDS programs have been prepared. The FDS-B program, which is one of these programs, manipulates the users' decision alternatives and decision objectives according to the described fuzzy membership functions. The FDS-M procedure, on the other hand, manipulates for the same decision environment to aggregate the individual decision ratings (decisions) to form a general representative decision for a group of experts.

. In addition to the FDS programs, another program is defined by using a hierarchical decision procedure. In this case, the decision alternatives are also rated with respect to each other. The program creates a decision environment and presents the procedure in a sequential way, so the user or the expert concentrates only on the rating of the parameters, not the decision procedure.

. The hierarchical decision procedure is similarly organised as FDS programs. The developed program is given as a generic compiler which creates a decision system to accept decision source files prepared according to the its compiler format. The expert then can prepare different files to describe different expertise in different conditions.

. After definition of the decision procedure, some of the analysis requirements become clear for the presented decision procedures. Therefore, a special type of decision support system, Exc-Dec has been created. The system works as an governing organiser, and if the user require a result from a certain analysis, such as numerical

analysis, graphical presentation procedure etc., that program is activated through the given system. The procedure is aimed to develop a real-time logic and conventional program interfacing project, but the current stage is available only for the interrupted solve-answer procedure. This means the user should interrupt the decision procedure to answer a question if extra calculation is required. The second method of decision procedure here is to answer all expected questions by activating all necessary conventional programs, then to activate the knowledge-based expertise transfer procedure to continue the expert defined decision.

. The first program given in this study as a conventional procedure is a database organiser for the material property storage. It keeps the laboratory and in situ test results of the materials for future usage.

. The second program prepared is for the definition of the rock mass classification. It handles seven rock mass classification methods. The engineer can either use them step by step or by using sequential data files for quick results from large numbers of inputs.

. The other conventional program is the discontinuity unit volume presentation which helps the engineers to understand the 3D structure of the discontinuities. The program is prepared to present the polar stereonet results of the give data sets in addition.

. Hudson's (Hudson, 1992) interaction matrix concepts are computerised and the cause and effect graphs are integrated with the excavation design procedure. The developed program presents the criticality and dominance of the decision parameters which can be used in the knowledge-base preparation.

. Numerical analyses are prepared by using the available solutions. The user interface for their data input and output interpretations has been developed to help engineers who do not have the necessary experience for numerical analysis interpretation. The developed program is available now with the given fixed mesh solutions, but it will be arranged according to user-defined numerical solution' mesh definitions.

. The prepared programs have been described and their usage demonstrated for the first time as a proposed excavation design procedure.

8.3 Recommendation For Further Research

The application of these methods at mining sites can indicate the requiremen· :e extra decision-support sub-program related with the cross-section definer, surface ι)ur analyzer statistical data simulator etc. In this respect full integration of the program should also be defined so the decision makers can analyse whatever they want to check without leaving the current decision questions. The compilers prepared for the NRS, NRS-CF, and NRS-FD decision analyses should be reviewed to develop a more user-friendly interface. The memory manager of the programs also should be examined in order to increase the number of neuro-conditions presented in each knowledge-base. The decision support programs should be prepared with more detail to illustrate all the fine points to examine what can go wrong in certain conditions. Then, full case studies can be conducted in parallel with real design to verify their total applicability. if, as expected, this proves successful, the total design package can be utilized as the main decision support system for rock engineering design.

APPENDIX C

LISTING OF PhD RESEARCH REPORTS PRODUCED BY THE ROCK MECHANICS RESEARCH GROUP AT IMPERIAL COLLEGE DURING PERIOD 1988-1994

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY & MEDICINE
UNIVERSITY OF LONDON, U.K.

PhD RESEARCH REPORTS (1988-94)
ROCK MECHANICS RESEARCH GROUP

The research in each of the following reports (see both sides of this sheet) was supervised by Professor J A Hudson and submitted via Imperial College for the degree of Doctor of Philosophy of the University of London.

Report 1 "A Fundamental Study of the Deformability of Rock Masses"
Wei Zhang Qing, June 1988, p. 268.

This report concerns the prediction of the deformability and strength of fractured rock masses. The work was stimulated by the need to understand anisotropy in rock mass properties caused by the presence of discontinuities, and has been extended to cover a variety of subjects associated with the fundamental behaviour of rock. The report contains the solution for the rock mass moduli as a function of an arbitrary array of discontinuities.

Report 2 "Computer Aided Risk Analysis of Open Pit Mine Slopes in Kaolin Mineral Deposits"
J P Kimmance, August 1988, p. 393.

This report is concerned with slope stability in difficult ground conditions, i.e. china clay deposits (which are kaolinised granite). The work described successfully integrates many rock engineering elements. The characterisation of the material properties via the use of geostatistics is one of the keys to slope stability in this ground.

Report 3 "Suggestion for Standardization of Rock Mass Classification"
D M Milne, August 1988, p. 165 (submitted for MSc degree on taught course)

This report is concerned with rock mass classification applied to underground mining, and is related to the general estimation of material properties as a guide to engineering. Because of the complexities of the rock mass and its associated material properties and boundary conditions, rock mass classification systems will be in use for decades ahead. (This report is included because of its value.)

Report 4 "Numerical Modelling of Rock Movements Around Mine Openings"
Pan Xiao-Dong, November 1988, p. 375.

This report is concerned with the prediction of rock mass movements around mine openings, and thus attempts to link material properties, boundary conditions, and excavation geometry and sequencing by numerical techniques. It covers analysis of individual subjects, analysis of coupled mechanisms, and the complete rock engineering problem, in this specific case the prediction of coal mine roof and floor movements.

Report 5 "*In Situ* Stress Indicators for Rock at Great Depth"
C G Dyke, December 1988, p. 361.

One of the most elusive and difficult boundary conditions in rock engineering is *in situ* stress. An approach is to coordinate all the separate indicators of the rock mass stress field — the approach discussed. Several of the issues involved are clarified and many of the 'indicator' techniques are explained in detail. A special study has been made of micro-crack induced strain relief processes. The work in tensor statistics will assist those wishing to understand how to reduce stress measurement data.

Report 6 "Development of a Knowledge Based System for Open Stope Design"
I W Harrison, September 1989, p. 268.

In this report, a first attempt is made to apply the relatively new concept of expert systems to the problems of open stope mine design. This work applies analyses of specific problems and coupled mechanisms to the solution of the complete rock engineering problem, in this case open stoping in the Carnmenellis granite in Cornwall, U.K.

Report 7 "The Potential State of Stress in a Naturally Fractured Rock Mass"
A J Hyett, January 1990, p. 365.

A highly creative and original piece of work examining the fundamental principles relating to *in situ* stress is presented, in particular the relation of stress state to geology. This report is a companion to Report # 5 "*In Situ* Stress Indicators for Rock at Great Depth" (see above). The report contains laboratory and numerical results and considers not only the stress boundary conditions in specific cases but also interactions with the rock mass geometry.

Report 8 "Investigation into the Mechanical Behaviour of Soft Rocks"
Wu Bailin, April 1991, p. 485.

Since the beginning of rock mechanics laboratory testing, rock samples have been compressed both uniaxially and triaxially to establish their mechanical behaviour. The interpretation of this behaviour has led to the establishment of elastic moduli, strength criteria, and an understanding of failure behaviour. The research reported here contributes greatly to this field. Useful discussion, test results and conclusions/recommendations are included.

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Report 9 *"In Situ* **Rock Stress Measurement"**
F D E Cuisiat, February 1992, p. 413.

This report continues the major group thrust on *in situ* stress and is related to the boundary conditions within which the rock engineer operates. It complements previous reports # 5 and # 7 which were related to specific methods of stress measurement and to the nature of stress itself. The main factors are integrated to provide a new framework for understanding the pre-existing state of stress in a rock mass. An oilfield case study is included.

Report 10 "Three-Dimensional Geometrical Analysis of Rock Mass Structure"
Y Ikegawa, February, 1992, p. 162.

Rock engineers are well aware that the naturally occurring fractures, the discontinuities, in a rock mass govern many of the rock properties — e.g. the local stress field, the deformability and the permeability. The work in this report advances the knowledge of methods for geometrically characterising planes in 3-D space and the associated blocks that are formed, and is extended to consideration of block removability criteria for complex geometries.

Report 11 "Investigation into the Cutting Process in Sandstones with Blunt PDC Cutters"
J R Almenara Chau, April 1992, p. 165.

This report is concerned with understanding the basic parameters that govern mechanical rock excavation using a drag pick — as applied to full-face tunnel boring machines, partial-face machines, or large drill bits. The work is considered to be a major advance in simplifying the models and associated rock parameter requirements.

Report 12 "Numerical Studies of the Hydro-Mechanical Behaviour of Jointed Rock"
Wei Lingli, September 1992, p. 296.

This report contains state-of-the-art coupled numerical analysis procedures that provide solutions to a wide variety of engineering geometries and rock mass circumstances. The subject is crucial for many engineering applications and the solution procedures are relevant for dam engineering, geothermal energy and radioactive waste disposal.

Report 13 "Developing Computer Methodologies for Rock Engineering Decisons"
M K Gokay, March 1993, p. 396.

As rock engineering problems become more complicated, it is essential to be able to handle all the knowledge requirements at all stages and scales within the problem. The work provides a complete review of the approaches that are possible. Specific programs were written for storing, presenting, and manipulating information in the rock mass classification context, and in connection with the new rock engineering systems approach.

Report 14 "Improved Analysis of Rock Mass Geometry Using Mathematical and Photogrammetric Methods" **J P Harrison, July 1993, p. 510.**

The work contains descriptions of novel laboratory equipment and mathematical methods for characterizing rock mass structure. A new stereo-photo-comparator has been developed for computerized discontinuity measurement, and fuzzy mathematics is used to develop improved methods of establishing the discontinuity clustering characterization. This work represents a major step forward in our ability to characterize rock mass structure.

Report 15 "The Development of a Rock Engineering Systems Methodology"
P N Arnold, July 1993, p. 377.

This is the first PhD on rock engineering systems — a methodology developed to enable all relevant parameters and mechanisms to be included in the rock engineering design. The report contains extensive discussion of all the factors, from an initial review of current practice and parameters used right through to the systems understanding of the total construction process. All the aspects of rock mechanics and rock engineering can be integrated with this methodology.

Report 16 "Neural Processing in Rock Engineering Systems"
D L Millar, Expected March 1994.

The relatively new techniques of neural processing are applied generally to rock engineering systems and specifically to the subjects of modelling the stress-strain behaviour of rock, assisting in computer-aided recognition of discontinuities, modelling rock mass behaviour and rock mass characterization. Neural networks are used to assist in the 'cognition' of rock parameters and mechanisms. Cellular automata for simulating rock behaviour are included.

Report 17 "Slope Instability in Weak Rocks — With Particular Reference to the Panama Canal"
M de Puy, Expected March 1994.

Regions of the banks of the Panama Canal have been unstable since the Canal was first opened earlier this century. We now have the opportunity to reassess the ground conditions and behaviour using modern numerical analysis and with much greater computing capability. In this report, the history of the canal constuction, together with the associated landslides, are reviewed. The geology, previous work and instablility history are reconsidered and reanalyzed.

Report 18 "Formalizing the Systems Approach to Rock Engineering"
Jiao Yong, Expected December 1994.

The interaction matrix enables the interactions between all the relevant parameters in a rock engineering problem to be listed out. These interactions can be quantified and mechanism pathways established by considering the interaction matrix as a network, and analyzing all the pathways using graph theory. This leads to the development of the 'fully-coupled' model, described here both mathematically and as applied to case examples.

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